ENERGY TRANSITIONS

Vaclav Smil

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ENERGY TRANSITIONS

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ENERGY TRANSITIONS

History, Requirements, Prospects

Vaclav Smil

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THE BOOK'S *RAISON D'ÊTRE*

The generic meaning of transitions—as passages from one condition or action to another—is quite straightforward and hence readily understood, but adding the energy qualifier complicates the comprehension. Energy, a concept that in itself is notoriously hard to define in an easy intuitive manner, encompasses a veritable universe of states and processes, and that is why the term *energy transitions* deserves some annotation. The focus should be always on a process, not just on its initial and concluding stages, but the most revealing analysis must deal with several key variables and use different measures to trace their change.

There is no formal or generally accepted hierarchy of meanings, but the term *energy transition* is used most often to describe the *change in the composition (structure) of primary energy supply*, the gradual shift from a specific pattern of energy provision to a new state of an energy system. This change can be traced on scales ranging from local to global, and a universally experienced transition from biomass to fossil fuels is certainly its best example. Many specific inquiries are possible within this grand shift: For example, the focus can be on transitions from wood to charcoal in heating, from coal to oil in households and industries, from oil to natural gas in electricity generation, or from direct combustion of fossil fuels to their increasingly indirect use as thermal electricity.

These studies of changing structure of energy supply often focus on the time elapsed between an introduction of a new primary energy source and its rise to claiming a substantial share (arbitrarily defined) of the overall market, or even becoming the single largest contributor or the dominant supplier on a local, national, or global scale. But given an often impressive growth of energy supply over time, close attention should be also given to absolute quantities involved in the transitions as well as to qualitative changes that result in wider availabilities of energies that are more flexible, more efficient, and more convenient to use even as they create substantially lower environmental impacts. Combination of all of these approaches would provide the best understanding of the transition process.

But the study of energy transitions should be also concerned with *gradual diffusions of new inanimate prime movers*, devices that had replaced animal and human muscles by converting primary energies into mechanical power. Focus on the prime movers also brings to the forefront the notion of a transition as a process of successful technical and organizational innovation, and energy transitions can be also studied as specific subsets of two more general processes of technical innovation and resource substitution. I will use all of these approaches in my examination of global and national energy transitions.

There is only one thing that all large-scale energy transitions have in common: Because of the requisite technical and infrastructural imperatives and because of numerous (and often entirely unforeseen) social and economic implications (limits, feedbacks, adjustments), energy transitions taking place in large economies and on the global scale are inherently protracted affairs. Usually they take decades to accomplish, and the greater the degree of reliance on a particular energy source or a prime mover, the more widespread the prevailing uses and conversions, the longer their substitutions will take. This conclusion may seem obvious, but it is commonly ignored: Otherwise we would not have all those repeatedly failed predictions of imminent triumphs of new sources or new prime movers.

And an inherently gradual nature of large-scale energy transitions is also the key reason why—barring some extraordinary and entirely unprecedented financial commitments and determined actions—none of today's promises for greatly accelerated energy transition from fossil fuels to renewable energies will be realized. A world without fossil fuel combustion is highly desirable and (to be optimistic) our collective determination, commitment, and persistence could hasten its arrival—but getting there will exact not only a high financial and organizational cost but also persistent dedication and considerable patience. As in the past, the coming energy transitions will unfold across decades, not years—and a few facts are as important for appreciating energy prospects of modern civilization as is an informed appreciation of this reality. This, in just half a dozen paragraphs, is the book's *raison d'être*.

Units and prefixes used in this book

Units

a	are	area
g	gram	mass
Hz	hertz	frequency
J	joule	energy
K	Kelvin	temperature
L	liter	volume
m	meter	length
m^2	square meter	area
m^3	cubic meter	volume
Mtoe	million t of oil equivalent	energy
N	newton	force
Pa	pascal	pressure
ppm	part per million	concentration
t	tonne (metric ton)	mass
W	watt	power
Wh	watt-hour	energy

Prefixes

h	hecto-	10^2
k	kilo-	10^3
M	mega-	10^6
G	giga-	10^9
T	tera-	10^{12}
P	peta-	10^{15}
E	exa-	10^{18}
Z	zetta-	10^{21}
Y	yotta-	10^{24}

Chapter 1

ENERGY SYSTEMS: THEIR BASIC PROPERTIES

Any anthropogenic energy system—that is any arrangement whereby the humans use the Earth's resources to improve their chances of survival and to enhance their quality of life (and, less admirably, also to increase their individual and collective power and to dominate, and to kill, others)—has three fundamental components: natural energy sources, their conversions, and a variety of specific uses of the available energy flows. The simplest systems in the past tapped only a small number of sources by using just one or two kinds of inefficient energy conversions for basic, and mostly precarious, subsistence, while modern systems can draw energy from numerous natural sources, convert them in many (and increasingly efficient) ways and use them in a myriad of ways in order to power complex high-energy societies.

Existence of the earliest hominin foragers was not that different from the survival of scavenging omnivorous animals as their somatic energy (conversion of food into muscle power) was just a segment of naturally cascading energy degradation beginning with solar radiation and ending with the dissipation of heat during walking, running, and gathering food. Our hominin ancestors may have used the first deliberate extrasomatic energy conversion as early as nearly 800,000 years ago by mastering the control of fire (Goren-Inbar et al., 2004). In contrast, modern high-energy societies tap many natural energy stores and flows, convert them by using some astonishingly sophisticated devices, and use them for purposes ranging from intensive food production to rapid long-distance travel. In today's world final per capita energy consumption ranges over two orders of magnitude, from the miseries of the sub-Saharan Africa to the excesses of the richest urban societies of America, Europe, and Asia. And in the most affluent societies even the average per capita energy use is now well beyond the level required for healthy and comfortable living.

All energy systems require infrastructures and their operation consumes considerable amounts of energy. Energy infrastructures comprise not only tangible components (exemplified by high-voltage transmission lines or pipelines) but—in order to extract, store, and process fuels and harness energy flows—they also include intangible organizational and managerial arrangements. Energy cost of energy is obviously a critical determinant of the viability of any energy system as only high-energy returns can create affluent societies with plenty of time left for leisure. These inescapable costs of energy are not measured in energy terms but are monetized as capital and operating costs. In the long run, most energy prices have shown some very impressive declines, particularly when compared in terms of actually delivered energy services (such as the cost of a lumen of light or a passenger-kilometer flown).

All anthropogenic energy systems also create environmental impacts, ranging from locally devastating deforestation to globally worrisome changes of the atmospheric composition, above all the emissions of CO_2, CH_4, SO_2, NO_x, and volatile organic compounds from fossil fuel combustion that have been responsible for increasing tropospheric temperatures, acid deposition, photochemical smog, and higher ground ozone levels. Some of the potentially highly damaging externalities arising from energy conversions have been either completely eliminated or reduced to acceptable levels by resorting to better production techniques and to efficient controls: Surface coal extraction and flue gas desulfurization are two excellent examples. Others, most notably the greenhouse gas emissions, are yet to be factored into the real cost of energy.

And, obviously, all energy systems evolve. During the preindustrial era there were only very slow changes in the composition of the primary energy supply (dominated by biomass fuels) and in the use of prime movers (dominated by human and animal muscles)—but the last two centuries have seen a series of remarkable energy transitions. These changes can be traced (and where statistics allow, be studied in revealing quantitative details) as shifts in the shares of individual fuels and in the origins of electricity generation as well as the adoption and diffusion rates of new prime movers and as new patterns of final energy uses. Scores of books could be consulted to get a more detailed understanding of the matters introduced in this chapter: Fouquet (2008), Smil (2003, 2008), and WEC (2007) might be convenient places to start.

RESOURCES AND PRIME MOVERS

Energies used by human societies can be classified dichotomously according to their origins either as renewable and nonrenewable or primary and secondary. Renewable energies include solar radiation (radiant or electromagnetic energy) and all of its biospheric transformations: plant mass (phytomass) formed by photosynthetic conversion of solar radiation into chemical energy of plant tissues; wind, arising from pressure gradients created by differential heating of the ground; moving water originating in radiation-driven evaporation and precipitation (stream flows) or as wind-driven waves and ocean currents; and the temperature difference between the surface of tropical oceans and dark cold waters below the thermocline (water layer, usually about 200 m thick, whose temperature fluctuates in contrast to deeper layers that stay at about 4°C). There is yet another renewable flux, the Earth's heat (geothermal energy) generated by the decay of heat-producing isotopes in the planet's crust and by heat rising from its core.

The spectrum of solar radiation contains the shortest gamma rays and x-rays, ultraviolet light (<400 nm), visible wavelengths (400–700 nm), and infrared (>700 nm). Nearly all of the UV wavelengths are screened by the stratospheric ozone layer, almost exactly 30% of the incoming radiation is reflected back to space and 20% is absorbed by the atmosphere; as a result, solar energy reaching the ground is only half of the solar flux in space. Active use of solar energy to generate electricity or to produce hot water is still rather limited, but all buildings have always benefited from passive solar heating, and architectural design can enhance this reality by optimizing the orientation of buildings, ingress of winter rays into rooms, and blocking of summer rays.

Photosynthesis uses only a small part of available wavelengths (principally blue and red light amounting to less than half of the energy in the incoming spectrum) and its overall conversion efficiency is no more than 0.3% when measured on the planetary scale and only about 1.5% for the most productive terrestrial (forest) ecosystems. Phytomass produced by photosynthesis is dominated by carbohydrates and absolutely dry phytomass has a fairly uniform energy density of about 18 MJ/kg; air-dry wood, the most important fuel for household heating and cooking and small-scale manufacturing in all preindustrial societies, contains about 15 MJ/kg, as do various cereal and legume straws and stalks that have been burned by households in arid and deforested regions.

Only a very small part of insolation (no more than 2%) energizes the global atmospheric circulation but the total power of winds generated by this differential heating is a meaningless aggregate when assessing resources that could be harnessed for commercial consumption because the Earth's most powerful winds are in the jet stream at altitude around 11 km above the surface, and in the northern hemisphere their location shifts with seasons between 30° and 70° N. Even at altitudes reached by the hubs of modern large wind turbines (70–100 m above ground) only less than 15% of winds have speeds suitable for large-scale commercial electricity generation. Moreover, their distribution is uneven, with the Atlantic Europe and the Great Plains of North America being the premiere wind-power regions and with large parts of Europe, Asia, and Africa having relatively unfavorable conditions.

Similarly, the total potential energy of the Earth's runoff (nearly 370 EJ, or roughly 80% of the global commercial energy use in 2010) is just a grand sum of theoretical interest: Most of that power can be never tapped for generating hydroelectricity because of the limited number of sites suitable for large dams, seasonal fluctuations of water flows, and the necessity to leave free-flowing sections of streams and to store water for drinking, irrigation, fisheries, flood control, and recreation uses. As a result, the aggregate of technically exploitable capacity is only about 15% of the theoretical power of river runoff (WEC, 2007), and the capacity that could be eventually economically exploited is obviously even lower.

There are four other water-based energy resources: tidal power and, as already noted, wind-driven waves, ocean currents, and the difference in temperature between the warm ocean surface and cold deeper waters. Each of them has a significant overall global potential but none of them is easy to harness. Large-scale tidal projects have remained in the conception/proposal stage for decades, wave-harnessing devices are in their early development stage, there have been no serious attempts to capture the power of major ocean currents, and even in the warmest tropical seas (where the difference between the surface and deep water surpass 20°C) the ocean thermal differences can be tapped for electricity generation only with a very low efficiency and none of a few isolated experiments with such generation had progressed to commercial projects.

Fossil fuels are by far the most important nonrenewable energies: All coals and most hydrocarbons (crude oils and natural gases) are transformations of ancient biomass, buried in sediments and processed by high pressures and temperatures (for millions to hundreds of millions of years), but a significant share of natural gases may be of abiogenic origin. All fossil fuels share the dominant presence of carbon, whose content ranges from nearly 100% in the best anthracite coals to 75% in methane; most common bituminous coals used in electricity generation, as well as most hydrocarbons, contain sulfur (a mere trace in some gases, up to 4% in some coals, with 2% being a common mean). Coals also contain varying shares of incombustible ash and moisture, as well as traces of heavy metals that are also present in many crude oils, and natural gases often contain dissolved nitrogen, water, and hydrogen sulfide.

Energy density of coals ranges from just 8 MJ/kg for low-quality lignites to about 30 MJ/kg for the best anthracites, with most bituminous (steam) coals between 20 and 25 MJ/kg. Crude oils are much more uniform (40–42 MJ/kg), as are the natural gases (mostly between 35 and 40 MJ/m^3). Resources of fossil fuels (their total mass present in the Earth's crust) are not known with a high degree of certainty, and their reserves (that part of resources that is recoverable with existing technical means and at profitable costs) keep changing as new techniques (such as horizontal drilling or steam-assisted recovery of oil from oil sands) lower their extraction cost to the point that previously uneconomical deposits become profitable sources of energies.

Resource recovery and depletion has engendered passionate debates about an imminent peak of global crude oil production, about the eventual magnitude of natural gas resources, and about the durability of coal deposits. What is not in doubt is that a large share of fossil fuel resources will be never exploited because their extraction and conversion would be technically forbidding or exceedingly costly: This is true about thin seams of poor-quality coal located at great depths as well as about many tiny hydrocarbon reservoirs or very heavy oils or deeply buried oil sands and oil shales. The same conclusion applies to fissionable materials abundant in very low concentrations in many rocks as well as in seawater.

Nuclear energy can be released either by fission of the isotopes of the heaviest natural elements (a process exploited in all nuclear electricity-generating plants) or by fusion of the lightest ones (a process whose commercial realization has been a frustratingly receding mirage). Since the late 1950s uranium fission has been used in commercial nuclear stations to generate electricity by the same means as in fossil-fueled stations (i.e., expanding the pressurized steam in a turbine that rotates a generator). In contrast, there are no fusion-based plants; none are even on a distant horizon and fusion may remain nothing but an ever-receding promise.

Division of energies into primary and secondary categories is based on the method of their production. Primary fuels (stores of chemical energy) are harvested (wood, crop residues) or extracted from the uppermost strata of the Earth's crust (all fossil fuels, including peats, coals, crude oils, and natural gases). Their combustion provides heat (thermal energy) or light (electromagnetic or radiant energy). Their processing to yield secondary fuels may change only their physical state (making solid briquettes by compressing coal dust, with or without binders), but it usually involves chemical transformation.

The only secondary fuel in preindustrial societies was charcoal made by pyrolysis (thermal decomposition in the absence of oxygen) of woody phytomass. With all volatile components driven out, the fuel is virtually pure carbon, nearly smokeless (its well-oxidized combustion produces only CO_2), and with high energy density of almost 30 MJ/kg (see Figure 1.1). Coke, made by high-temperature pyrolysis of coal, was first used in England during the 1640s in malt roasting, but only when its cost declined sufficiently did it begin to replace charcoal as a fuel in blast furnaces by the middle of the eighteenth century, and it has remained the fuel of choice for all primary iron production ever since. During the nineteenth century another secondary fuel—coal gas (town gas or manufactured gas)—became a common urban illuminant (in- and outdoors) as well as a fuel for cooking; it was eventually displaced by electric lights and natural gas, but in some cities its use lingered until after World War II.

Today's most important, as well as by far the most common, secondary fuels are various liquids produced by refining crude oils. Refining was done initially by simple thermal distillation (fractions separated by temperature); now the crude oils are transformed with the help of catalytic cracking used to produce higher shares of gasoline and jet fuel (kerosene), lighter and more valuable fuels that power passenger cars and airliners. Heavier diesel oil is also used to fuel cars but its principal consumer is truck and railways transport, while the heaviest residual oil powers the marine transportation. Diesel oil and residual fuel oil are also used in stationary generation of electricity.

Figure 1.1 Steps in preparing wood piles for charcoaling illustrated in Diderot and D'Alembert's *L'Encyclopédie* (1769–1772).

Commercial electricity generation and transmission added a new dimension to human energy use and, as in the case of fuels, electricity's origin is classified as either primary or secondary. Primary electricity involves all conversions of natural, renewable energy flows including those of water and wind, the Earth's heat, and solar radiation. Primary electricity could also be generated by harnessing ocean waves and the temperature differences between the surface layer of the warmest ocean and constantly cold waters underneath. Nuclear electricity is yet another form of primary energy, with steam for large turbogenerators derived from controlled splitting of uranium. Secondary electricity uses heat released from the combustion of fossil fuels, mainly coal for steam turbogenerators and natural gas for gas turbines.

Prime movers are energy converters able to produce kinetic (mechanical) energy in forms suitable for human uses. Human muscles (somatic energy) were the only prime movers (converting chemical energy in food to kinetic energy of walking, running, and countless manual tasks) until the domestication of animals provided more powerful animate prime movers used in fieldwork, transportation, and for some industrial tasks. Animate prime movers continued to dominate energy use long after the introduction of first mechanical prime movers, beginning with simple sails, followed, millennia later, by small water wheels, and roughly another millennium afterwards by small windmills.

During the eighteenth century the steam engine became the first mechanical prime mover powered by the combustion of fuels. Steam turbine and two key types of internal combustion engines (sparking gasoline-fueled machine and non-sparking engine fueled by heavier fuels or by residual oils) were invented before the end of the nineteenth century, and gas turbine became practical during the 1930s. Electric motors present a classification dilemma: They are, obviously, prime movers in the sense of the definition I offered at the outset of the preceding paragraph, but they are powered by electricity that has been produced by prima facie prime movers, be it steam turbogenerators or gas, water, and wind turbines.

Major criteria used to classify energy uses, as well as the deployment of prime movers, are the location of the conversion process, temperature of the final use, and principal economic sectors. Stationary combustion provides space heating for households, public institutions, and industries, as well as hot air and steam for industrial processes. Stationary prime movers (dominated by steam turbogenerators and water turbines) produce the world's electricity and electric motors and internal combustion engines power most of the modern industrial processes. Heavy horses were the most powerful commonly used mobile prime movers in preindustrial societies. Mobile steam engines, introduced between 1805 and 1835, revolutionized both land and water transportation and dominated the two sectors until the middle of the twentieth century.

Mobile steam turbines were first used in ship propulsion at the beginning of the twentieth century, but marine transport became eventually dominated by diesel engines. Diesels also power heavy road transport and a variety of off-road vehicles, while the automotive gasoline-fueled internal combustion engines emerged as the world's most numerous mobile prime movers. Commercialization of gas turbines began during the late 1930s but their widespread adoption had to wait until the 1960s. Larger stationary machines are used mostly in electricity generation and, starting in the 1950s, lighter and increasingly powerful gas turbines rapidly displaced reciprocating internal combustion engines in long-distance air travel. During the 1980s modified jet engines began to be used also for stationary applications as aeroderivative turbines for peak demand or decentralized electricity generation.

CONVERSIONS AND USES

Modern societies use many forms of energy in order to satisfy many final uses. While there is no single binding classification of the uses that provide individuals, households, cities, and economies with essential energy services, the principal categories include heat, light, industrial (overwhelmingly stationary) power, and freight and passenger transport. All energy conversions involve some loss of the capacity to perform useful work. This is the essence of the second law of thermodynamics: in any closed system (i.e., one without any external supply of energy), availability of useful energy can only decline. Energy remains conserved (the first law of thermodynamics) but its practical utility is diminished because disordered, dissipated low-temperature heat (the final product of all energy conversions) can be never reconstituted as the original, highly organized fuel or electricity. This is an irreversible process, as no action can reconstitute a tank full of gasoline or a truckload of coal from the diffuse heat in the atmosphere.

While such considerations as comfort and convenience are hardly unimportant, the quest for higher conversion efficiencies underlies the evolution of modern energy systems. The simplest definition of energy conversion is as the ratio of output or transfer of the desired energy kind achieved by a converter to the initial energy input (be it to an organism, a mechanical device or a complex system). This rate does not capture the efficiency limitations due to the second law. The second-law (or exergy) efficiency is expressed as the ratio of the least available work that could have performed the task to the available work that has been actually used in performing it. This measure provides a direct insight into the quality of performance relative to the ideal process, and it is concerned with a task to be performed, not with a device or a system used for that end.

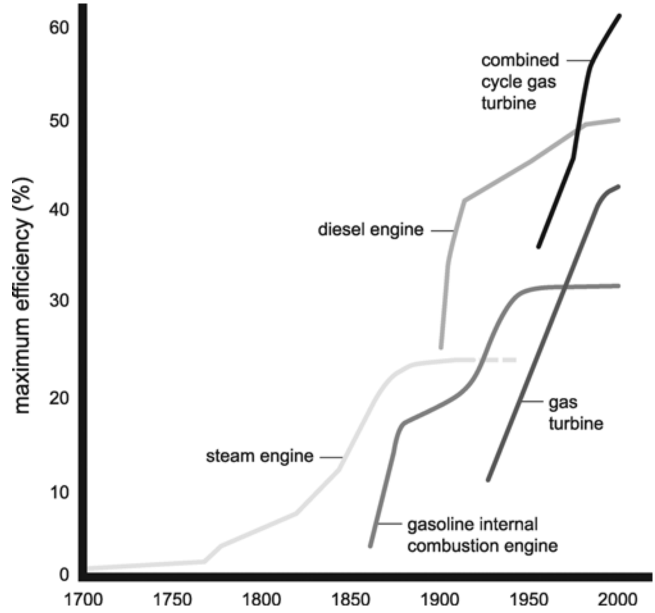
As a result, all conversions using high-temperature combustion (flame in excess of 1200°C) to supply low-temperature heat (to pasteurize food at 72°C, to heat bath water to no more than 49°C in order to avoid third-degree burns) will be particularly wasteful when judged in terms of the second-law efficiency. But, as the following examples show, applying that efficiency to many human actions may be actually irrelevant or inappropriate. One of the most efficient ways to produce animal protein is carp aquaculture (as those cold-blooded herbivorous species have inherently low metabolic needs) while the most inefficient way to produce animal protein is beef from cattle fed a mixture of corn and soybeans in a giant feedlot. But most people with good incomes prefer to buy beef, not carp. Similarly, corn is the most efficient staple grain crop—but unlike gluten-rich hard wheat, its flour cannot be used to bake leavened breads. And a periodic bleeding of cattle by Kenya's Maasai is a vastly more efficient means of converting grasses to food than slaughtering cattle for meat—but how many societies would be ready to make such a switch?

Combustion, that is, rapid oxidation of carbon and hydrogen in biomass and fossil fuels, has been the dominant energy conversion since the early stages of human evolution. For hundreds of thousands of years of hominin evolution it was limited to wood burning in open fires, and combustion of biomass fuels remained the principal means of securing heat and light until the advent of industrialization—and even the most advanced of today's postindustrial societies derive most of their useful energies from the burning of fossil fuels. What has changed, particularly rapidly during the past 150 years, are the typical efficiencies of the process. In open fires less than 5% of wood's energy ended up as useful heat that cooked the food; simple household stoves with proper chimneys (a surprisingly late innovation) raised the performance to 15–20%, while today's most efficient household furnaces used for space heating convert 94–97% of energy in natural gas to heat.

The earliest commercial steam engines (Newcomen's machines at the beginning of the eighteenth century) transferred less than 1% of coal's energy into useful reciprocating motion—while the best compound steam engines of the late nineteenth century had efficiencies on the order of 20% and steam locomotives never surpassed 10% (see Figure 1.2). The first internal combustion engines (stationary machines powered by coal gas) had lower efficiencies than the best contemporary steam engines, and even today's best-performing gasoline-fueled engines do not usually surpass 25% efficiency in routine operation.

But the very first working prototype of Rudolf Diesel's non-sparking engine (officially tested in 1897) surpassed that rate and the world's largest marine diesel engines are now the only internal combustion machines whose efficiency can reach, and even slightly surpass, 50%. For comparison, today's best gas turbines (used in aviation and electricity generation) are about 40% efficient (Figure 1.2). When the hot gas ejected by large stationary gas turbines is used to heat water for a steam turbine, this combined cycle gas turbine can reach overall efficiency of about 60%. In contrast, the maximum efficiency of coal-fired electricity-generating

Figure 1.2 Maximum efficiency of prime movers, 1700–2000. There has been an order of magnitude gain during the last two centuries, from about 6% for steam engines to about 60% for the combined-cycle gas turbines.



plants using the standard configuration of a boiler and a steam turbogenerator is just over 40%.

Rising efficiency of individual conversions has been reflected in the improving performance of entire economies. As a result, the difference between average per capita energy use in modern and traditional societies is significantly greater when compared in useful terms rather than as the rates of gross energy consumption. For example, thanks to a relatively easy access to extensive and rich forests, the average U.S. wood and charcoal consumption was very high: about 100 GJ/capita in 1860, compared to about 350 GJ/capita for all fossil and biomass fuel at the beginning of the twenty-first century. But as the typical 1860 combustion efficiencies were only around 10%, the useful energy reached only about 10 GJ/capita. Weighted efficiency of modern household, industrial, and transportation conversions is about 40% and hence the useful energy serving an average American is now roughly 150 GJ/year, nearly 15-fold higher than during the height of the biomass era.

Energy uses have undergone some significant changes even during the preindustrial period when most fuels were used by households and in small-scale artisanal manufactures, and when most prime movers were deployed in subsistence agriculture. Expansion of manufactures and metallurgy led to a spreading use of water power (most efficiently by larger vertical water wheels) and iron metallurgy and the preference for smokeless fuel in richer urban homes had also created higher demand for charcoal. Crop rotations including leguminous food and cover crops enabled farmers to divert a greater share of harvests to animal feeding and made it possible to deploy larger numbers of more powerful animals in agriculture.

Industrialization brought a radical change in the composition of national energy use as coal mining, metallurgy, and heavy machinery sectors became eventually the leading consumers of energy, followed by light manufactures (textiles and various consumer items) and a rapidly expanding land and sea transportation. In Europe and North America this shift was accomplished already before 1900. Households claimed a relatively small share of overall energy use during the early phases of industrialization, first only as coal (or coal briquettes) for household stoves, later also as low-energy coal (town) gas, and (starting during the 1880s) as electricity for low-power light bulbs, and soon afterwards also for numerous household appliances.

Subsequently, modern energy use has seen a steady decline of industrial and agricultural consumption and increasing claims of transportation and household sectors. For example, in 1950 industries consumed more than half of the world's primary commercial energy, at the time of the first oil crisis (1973) their share was about one-third, and by 2010 it declined to about 25%. Major appliances (refrigerators, electric stoves, washing machines) became common in the United States after World War I, in Europe only after World War II, and private car ownership followed the same trend. As a result by the 1960s households became a leading energy-using sector in all affluent countries. There are substantial differences in sectoral energy use among the industrializing low-income nations and postindustrial high-income economies. Even after excluding all transportation energy, U.S. households have been recently claiming more than 20% of the country's primary energy supply in 2006, while in China the share was only about 11%.

But the boundaries of standard sectoral classification can be redrawn to yield a different breakdown. Perhaps most notably, modern agriculture consumes directly only a few percent of the total energy supply as fuels and electricity to operate field machinery (tractors, combines, irrigation pumps) and mostly as electricity for heating, cooling, and machinery used in large-scale animal husbandry. But the indirect energy cost of agricultural production (to produce agricultural machinery, and to synthesize energy-intensive fertilizers, pesticides, and herbicides) and, even more so, energy costs of modern industrial food processing (including excessive packaging), food storage (the category dominated by refrigeration), retailing, cooking, and waste management raise the aggregate cost of the entire food production/distribution/preparation/disposal system to around 15% of total energy supply.

Inevitably, changing sectoral requirements have affected the final uses. Before the advent of extensive steam-driven electricity generation (during the 1890s), coal had four major final uses: as the leading household fuel, as the principal source of both process heat and steam and mechanical power in industries, as the prime energizer of land and water transport, and as the feedstock to produce metallurgical coke needed to smelt pig iron. A century later, coal ceased to be an important transportation fuel, only in a few countries was it still used for household heating and cooking, and its rising use was confined largely to only two markets, the dominant one for electricity generation and a smaller one for coke production.

Similarly, refined oil products were used first as illuminants and lubricants and only the mass ownership of cars (the era that began in the United States with Ford's Model T in 1908) required mass production of gasoline. After World War I diffusion of Diesel's efficient engine in trucking and shipping claimed the heaviest fuel oils, and the post–WWII commercialization of jet engines made kerosene the third most important refined product. And natural gas became the world's premiere source of household heat only after 1950. There were also some notable shifts in non-energy uses of fuels: During the late nineteenth century coal became an important feedstock for chemical industries, but its use was soon displaced by crude oil and natural gas. Currently on the order of 10% of all extracted oil and slightly more than 5% of all natural gas are used as chemical feedstocks, above all for syntheses of ammonia and various plastics.

Another revealing classification that ignores the traditional sectoral divisions is according to the prevailing temperature of final uses. Most energy needs are for low-temperature heat, dominated by space heating (up to about 25°C), hot water for bathing and clothes washing (maxima of, respectively, about 40°C and 60°C), and cooking (obviously 100°C for boiling, up to about 250°C for baking). As already noted, ubiquitous heat waste is due to the fact that most of these needs are supplied by high-temperature combustion of fossil fuels. Steam and hot water produced by high-temperature combustion also account for 30–50% of energy needs in food processing, pulp and paper, chemical and petrochemical industries. High-temperature heat dominates metallurgy, production of glass and ceramics, steam-driven generation of electricity, and operation of all internal combustion engines.

INFRASTRUCTURES AND IMPACTS

Only the simplest harnessing and conversion of energies (gathering of woody debris and its burning in primitive stoves) does not require special infrastructures whose existence must either precede a particular form of energy use or must accompany its expansion. Some early infrastructures could be relatively simple. For example, in the eighteenth century an unpaved road leading to a coal seam outcropping in a previously uninhabited valley would make it possible to bring in the material necessary for opening a small mine and to haul the mined coal in horse-drawn wagons to the nearest settlement. But a large nineteenth century mine would have to be connected to its markets by a railroad, or its coal would be shipped by barges, and the mining of deeper seams could not be accomplished without first installing adequate steam-powered water pumping and ventilation facilities.

Infrastructural needs reached an entirely new level with the exploitation of hydrocarbons whose large-scale extraction requires complex and expensive infrastructures. Pipelines are needed to carry the crude oil and natural gas to markets (or to the nearest coast for overseas exports) and a pretreatment (separation of water, brine, petroleum gases, or hydrogen sulfide) may be required before sending such fuels by a pipeline. When natural gas is used for household heating it is necessary to have voluminous storages to meet high winter peak demand. Crude oil is too valuable a resource to be burned as is and it needs expensive refining that converts it into gasoline, kerosene, diesel oil, residual oil, and non-energy products (lubricants, paving materials).

Electricity generation presents an even more demanding case of infrastructural prerequisites. Not only it is necessary to have extensive networks of transmission and distribution lines in place before any large-scale generation can take place, it is also necessary to have large numbers of converters (lights, appliances, electric motors, electric furnaces, electrochemical processes) ready to use the delivered electricity. Consequently, size of electricity-generating stations has been driven by rising demand—and it has been also constrained by the existing (and anticipated) load. For example, the maximum size of turbogenerators in the U.S. thermal stations stopped growing (and the average size had actually declined) as the demand weakened during the 1970s. Perhaps the most exacting infrastructural challenge has been presented by the exports of liquefied natural gas (LNG). High costs of liquefaction plants, LNG tankers, and regasification facilities mean that the economies of scale dictate the construction of a system capable to deliver at least a million tonnes of gas a year.

Energy systems have also become more interdependent and their integration has been steadily expanding. Preindustrial energy systems were just patchworks of independent entities. Their spatial extent could have been as small as a village that relied on nearby forests and on crop residues for all of its fuel and feed needs and that produced virtually all of its food by growing a variety of crops in rotations. Modernization began to enlarge the boundaries of energy systems, first with railway and shipborne transport of coal, then with increasingly large-scale production of industrial manufactures that were traded not only nationwide but even overseas and with adoption of simple agricultural machines.

Today's energy system is truly global, with nearly 50 countries exporting and almost 150 nations importing crude oil (and with nearly as many trading refined oil products), with more than 20 states involved in natural gas sales (either by cross-border pipelines or by using tankers carrying liquefied gas), and with nearly a dozen major coal importers and a similar number of countries with substantial coal imports. Electricity is traded relatively less than coal, but even so at least two dozen countries have interconnections of sufficient capacity to carry on exchanges on a GW scale. Moreover, there are no national autarkies as far as extraction, transportation, and processing of energy is concerned: Mining machinery, oil and gas drilling rigs, pipelines, tankers, and coal-carrying vessels and refineries are designed and made by a relatively small number of producers in about a score of countries and used worldwide.

And design and production of the most powerful prime movers have seen an even greater degree of concentration, with as few as two or three companies dominating the global market. All of the world's largest marine diesel engines that power virtually all large commercial vessels (oil and gas tankers, bulk carriers, container ships) come from the duopoly of MAN Diesel and Wärtsilä (and the companies license their engines to a small number of makers in Europe and Asia) and all of the world's most powerful jet engines are designed and made by America's General Electric and Pratt & Whitney and Britain's Rolls-Royce, or by alliances of these companies.

Because of energy's central place in nature and in human affairs it is inevitable that the massive burning of fossil fuels, fissioning of uranium, and capture of renewable energy flows have many profound consequences for the performance of economies and for the state of the environment, and hence for the overall quality of life. Consequently, it is incredible that energy has never been a primary, not even a major, concern of modern economic inquiry. This also helps to explain why modern societies began to deal with widespread environmental impacts of energy use only after World War II. Modern studies of energy–economy links have uncovered some broad commonalities that have marked the path from traditional to industrial to postindustrial societies—but they are perhaps no less notable for revealing many singularities and peculiarities. Environmental impacts of energy use are often so difficult to appraise because there can be no generally acceptable metric for valuing their consequences for biota, climate, and human health.

Global growth of primary energy consumption has corresponded fairly closely to the expansion of the world's economic product: During the twentieth century a roughly 17-fold expansion of annual commercial energy use (from about 22 to approximately 380 EJ) produced a 16-fold increase of annual economic output, from about $2 to $32 trillion in constant 1990 dollars (Maddison, 1995; World Bank, 2001). Similarly close relationship is revealed by studying historical statistics of many individual countries—but comparisons among the countries clearly indicate that a given level of economic development does not require an identical, or not even very similar, level of the total primary energy consumption. This is true among low-income economies as well as among affluent nations: France has certainly a much higher standard of living than Russia even though the two countries consume primary energy at a very similar per capita rate.

Fewer exceptions are found as far as the secular decline of average energy intensity (energy use per unit of GDP) is concerned. That rate's rise during the early stages of industrialization (reflecting energy needs for new industrial and transportation infrastructures) is usually followed by a prolonged decline. The British peak came early in the nineteenth century, the U.S. and Canadian peaks followed six to seven decades later—but Japan reached its highest energy intensity only in 1970, and China's energy use per unit of the country's GDP continued to rise until the late 1970s but since that time the Chinese rate has fallen faster than in any previous case: By 1990 it was 40% below the 1980 level, and by 2005 the decline reached just over 70% (Fridley et al., 2008). But comparisons of national energy intensities and their secular trends require careful interpretation because their differences are caused by factors ranging from climate to consumer preferences, with the composition of primary energy consumption and the structure and efficiency of final conversions as key factors.

Countries with harsh climate, generously sized houses, large territories, and numerous energy-intensive industries will have relatively high national energy intensities even if their specific energy conversions are highly efficient, while countries undergoing modernization will have much higher intensities than postindustrial economies. These realities help to explain why, for example, Canada's energy intensity is more than twice as high as that of Italy, and China's intensity is still more than twice that of Japan. Another long-term trend has been the decarbonization of the global energy supply: The relative shift away from coal (usually more than 30 kg of carbon/GJ) to liquid hydrocarbons (averaging about 20 kg C/GJ) and natural gas (less than 15 kg C/GJ) and rising generation of carbon-free primary electricity had lowered the carbon content of the world's primary energy supply by about 25% during the twentieth century, and the slowly increasing share of renewable conversion will continue to lower that rate.

Technical innovation, economies of scale, and competitive markets have combined to bring some impressive long-term declines of energy prices, particularly when compared to rising disposable incomes or when expressed in terms of value for delivered service. None of these declines has been more impressive than the cost of electricity for lighting traced as constant monies per lumen: Fouquet (2008) found that rising incomes, higher conversion efficiencies, and lower generation costs made the household lighting in the United Kingdom in 2000 about 160 times more affordable than in 1900. In contrast, inflation-adjusted prices of coal and oil do not show a general declining trend but a great deal of fluctuation and a remarkable constancy in the long run. When expressed in constant monies crude oil prices were very low and very stable between the beginning of the twentieth century and the early 1970s, they retreated rapidly after two OPEC-driven price rises of 1973–1974 and 1979–1981, but their recent fluctuations offer no safe foundation for looking ahead.

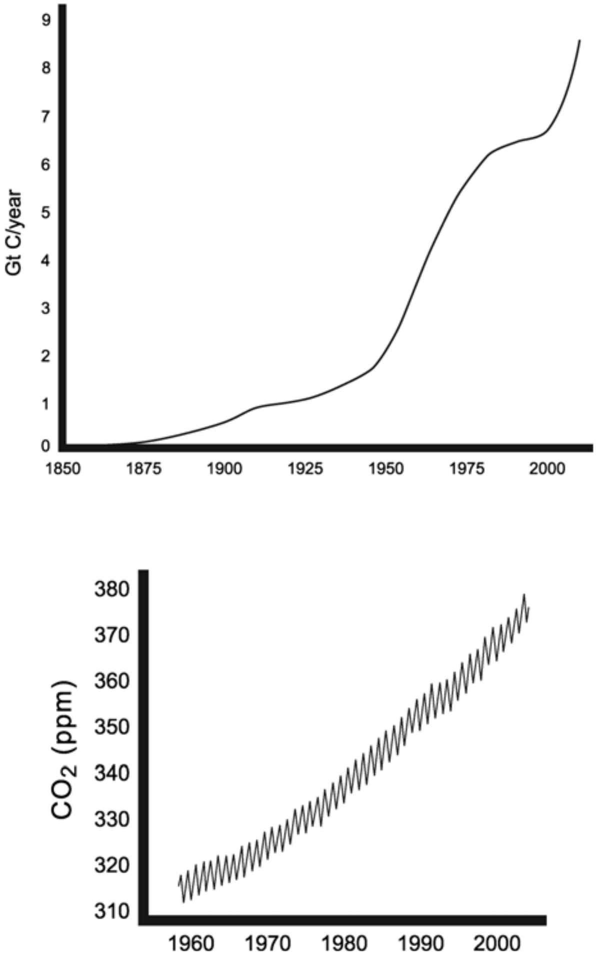
But energy prices have not been usually determined by free-market operation, as energy industries in general (and oil industry and nuclear electricity generation in particular) have been among the greatest beneficiaries of government subsidies, tax breaks, and special regulation. Some prices have been subject to cartel control: In the United States the Texas Railroad Commission fixed prices by allocating production quotas until March 1971, and since 1973 OPEC has used its production quota to manipulate the global crude oil supply. Even more importantly, no energy price expresses the real cost of the delivered service, as the costs of often significant environmental and health externalities are not included in the prices of fuels or electricity.

Internalization of these costs has been done adequately in some cases (electricity cost is higher due to highly efficient capture of particulate matter by electrostatic precipitators and removal of SO_2 by flue gas desulfurization; all modern passenger cars have three-way catalytic converters to reduce NO_x, CO, and volatile organic hydrocarbon emissions) but it remains a challenge in most instances, above all because health effects account for most of the cost but are notoriously difficult to monetize—as are the long-term ecosystemic effects of such complex processes as photochemical smog, acid deposition, nitrogen enrichment, or climate change. Strategic considerations further complicate the quest for the real price of energy: Perhaps most notably, the Pentagon had been devoting a significant share of its budget to the Middle East even before the 1991 Gulf War or before the Iraqi invasion of 2003.

As for the environmental impacts of energy industries and uses, it is clear that the anthropogenic emissions of CO_2 from the combustion of fossil fuels have become one of the most prominent concerns of modern civilization.

Their global total rose from just over 0.5 Gt C in 1900 to nearly 8.5 Gt C by 2007, and they have been the major reason (deforestation, mainly in the tropics, was the second most important contribution) for the rise of tropospheric CO_2 concentration (since 1957 continuously monitored at the Mauna Loa observatory in Hawaii) from about 295 ppm in 1900 to 386 ppm by 2008 (Figure 1.3). This is a truly global phenomenon, as the average tropospheric concentrations rise no matter where the emissions take place. After being the leading emitter for more than a century, the United States was surpassed in 2007 by China (but in per capita terms there is a nearly four-fold difference).

Figure 1.3 Global emissions of CO_2, 1850–2008 (in Gt C/year) and tropospheric CO_2 concentrations, 1958–2008. Plotted from emissions data in Rotty and Marland (2009) and from Mauna Loa concentrations data in NOAA (2009).



Extraction and conversion of energy has many other environmental consequences. Deforestation in the Mediterranean and in North China was the first environmental manifestation of the growing human use of energy as emerging cities and expanding metal smelting (first copper, then iron) needed more wood and charcoal. Underground coal mining created aboveground disturbances (subsidence, mountains of mine spoils) and localized water pollution (acid runoff), but emissions of particulate matter and SO_2 were the most important environmental consequences of coal combustion as the two pollutants often reached very high concentrations in large cities. After 1950 electrostatic precipitators virtually eliminated particulate pollution from large sources but long-distance transport of SO_2 (and also NO_x) created serious regional to semi-continental problems with acid deposition.

Extraction and transportation of crude oil created local water pollution and accidental oil spills, and combustion of refined oil products provided the key starting ingredients (NO_x, CO, and volatile organic compounds) for photochemical smog. Beginning in 1956 generation of electricity by fissioning uranium introduced an entirely new set of environmental problems, ranging from possibilities of accidental contamination to challenges of long-term storage of high-level radioactivity waste. And renewable energy flows have a multitude of their own environmental consequences, ranging from the alterations of water quality and age caused by large dams (lower temperature, water aging behind dams) to problems with esthetic acceptability of large wind turbine farms and with their noise and effect on birds.

ENERGY TRANSITIONS

As this brief review of energy system fundamentals makes clear, there are many components whose importance and performance evolve and hence there are many energy transitions whose origins, progress, and accomplishments can be studied on levels ranging from local to global. Not surprisingly, transitions to new energy sources (be they gradual diffusions of new fuels or new modes of electricity generation) have attracted a great deal of attention and I will quantify the key shifts—from wood and charcoal to coal and then to hydrocarbons, followed by transitions to a higher share of primary energies consumed in a secondary form as electricity—from the global perspective as well as by focusing on some notable national trajectories.

Perhaps even more attention has been paid by the historians of technical advances to the diffusion of new fuel and electricity converters ranging from better stoves and lights to more efficient furnaces and boilers, with particular interest in the evolution and diffusion of new engines and turbines and new electricity-powered motors and appliances. Technical innovation, emergence of new mass energy markets, and a steadily rising demand for more efficient, more affordable, and more flexibly delivered energy services were both the driving factors behind these changes and, thanks to numerous reinforcing feedbacks, also their beneficiaries.

In addition to tracing the transitions to new energy sources and new energy converters it is also revealing to look at the changing uses of individual fuels (most notable, coal losing all of its transportation markets but becoming the leading fuel for electricity generation, and the principal use of refined oil products shifting from illuminants and lubricants to transportation fuels) and at changing patterns of sectoral consumption. The latter shifts are actually an excellent means of tracing a nation's trajectory of modernization and its rise to affluence: Diversification of final commercial energy uses proceeds from the initial pattern dominated by industrial consumption to a combination characterized by the absence of any dominant use, where each of the four key sectors (households, industries, commerce, and transportation) claims a major share of the final demand.

As this book's principal aim is a comprehensive appraisal of energy transitions—on levels ranging from global to national and looking at trends ranging from aggregate provision of primary energies to specific supplies of individual fuels and progress of important conversion techniques—I will use this introductory section only in order to make several general observations by resorting to analogies. When appropriately understood—that is, in an illuminating, suggestive manner and not as rigid templates—analogies are a useful tool to emphasize important features of a complex process. I think that two of them, of widely differing provenience, are particularly relevant to the understanding of energy transitions.

The first one draws on Tolstoy's famous observation (in *Anna Karenina*) regarding families: "Happy families are all alike; every unhappy family is unhappy in its own way." Analogically, notable similarities can be seen when looking at all rapid and apparently easily accomplished energy transitions—while the reasons for prolonged, complicated, and delayed transitions are usually very specific, bound with unique environmental, social, economic, and technical circumstances. Rapidity of energy transitions is most evident when looking at small countries with compact territories that have either relatively few people or a high density of population. No matter if they are affluent economies or still essentially premodern societies with very low per capita economic product, once they discover a new rich source of primary energy they can develop it rapidly and end up with completely transformed energy foundations in less than a single generation.

The Netherlands—thanks to the discovery of a giant Groningen natural gas field in the municipality of Slochteren in the northern part of the country on July 22, 1959 (Whaley, 2009)—is perhaps the most apposite example of an affluent economy following this path (for more detail, see chapter 3), while Kuwait's rapid development of its giant oilfields is an iconic example in the second category. Kuwaiti oil development began only in 1934 with the concession given to the Kuwait Oil Company, a joint undertaking of the APOC (Anglo-Persian Oil Company, later BP) and Gulf Oil. The concessionary agreement was signed after the APOC was assured by an expert it hired to evaluate the country's oil prospects that "the absence of geological structure suitable for the accumulation of oil in commercial quantity shows that there is no justification for drilling anywhere in Kuwait" (Howard, 2008, p. 152).

At that time that small country (with an area less than half that of the Netherlands) was an impoverished British protectorate with fewer than 100,000 people, a single town, and mostly empty interior with a small number of desert nomads; export of pearls, harvested by diving, was declining and traditional maritime trading (horses, spices, coffee) was the only notable economic activity. The concession was signed on December 23, 1934, and the supergiant al-Burqān oilfield (a Cretaceous sandstone trapped above a massive swell of about 750 km^2 of salt) was discovered on February 23, 1938. The field was later proved to be the world's second largest accumulation of oil, following the Saudi al-Ghawār (Stegner, 2007; Howard, 2008). In 1946, when it began its oil exports, Kuwait produced about 800,000 t of oil, a year later 2.25 Mt, annual output surpassed 50 Mt by 1955 and 100 Mt by 1965 when the country was, ahead of Saudi Arabia, the world's fourth largest producer of oil (behind the United States, USSR, and Venezuela). In energy terms Kuwait thus moved from a premodern society dependent on imports of wood, charcoal, and kerosene to an oil superpower in a single generation.

In contrast, large economies, particularly those with relatively high per capita demand and with extensive infrastructures serving an established fuel, cannot accomplish the substitutions so rapidly. Comparing the Dutch and the British experience is particularly revealing in this respect, as both of these countries benefited from major natural gas discoveries. The first discoveries of natural gas in the British sector of the North Sea were made by BP in 1965 but despite an aggressive development of those rich and relatively near-shore deposits, Britain could not accomplish even in 30 years what the Netherlands did in a decade: Its share of natural gas stood at a bit less than 5% of the primary energy supply in 1970 and it peaked only 30 years later at about 39%.

Principal reasons for the difference include a much higher total of the absolute supply needed to provide an identical share of the primary energy (by 1970 the UK's primary energy supply was nearly 220 Mtoe/year compared to 60 Mtoe/year in the Netherlands), UK's traditionally high dependence on coal-fired electricity generation, the country's pioneering role in nuclear generation (it would have been very costly to shut down those stations and replace them with gas-fired plants), a higher cost and longer lead times to develop offshore resources rather than hydrocarbons fields on land (particularly in such an inhospitable environment as the North Sea), and also the much larger size of the country (about 244,000 km^2) necessitating longer trunk and distribution lines.

And the Japanese progress shows that when the gas has to be imported from overseas then the pace of substitution must be even slower—regardless of the fact that the country was one of the pioneers of LNG imports (starting in 1969 with *Polar Alaska* and *Arctic Tokyo*, each with capacity of 71,500 m^3 to carry gas from Alaska) and that when it commenced its LNG imports it was not only one of the world's leading economies but one with an enormous experience in shipbuilding. At the same time, a slow pace of substitution comes as no surprise given the size of Japan's economy and its nearly total dependence on fossil fuel imports: This means that despite its relatively high efficiency the country now requires annually more than 500 Mtoe (nearly 22 EJ) of primary energy. Given these circumstances Japan's LNG progress could be actually seen as rather impressive, as the country had increased the share of natural gas in its energy supply from 5% in 1979 to about 16% by 2008.

The second analogy illuminating the process of energy transitions is their comparison with aircraft accidents. Careful studies of those events show that they are nearly always due to a number of factors and that the final outcome is a result of a specific sequence of errors (be they actions or inactions) taken by crews in response to a sudden change, be it a faulty indicator light, erroneous instrument reading, or (an increasingly rare occurrence with modern gas turbines) mechanical failure of one or more of the airplane's engines. And so it is with energy transitions: They are never brought about by a single factor, and in the second chapter I will show that this was the case even with perhaps the most commonly cited claim, portraying English wood shortages as the decisive factor forcing the country's early transition to coal.

And, as with the aircraft accidents, a careful investigation of energy transitions always reveals that their progress requires a specific sequence of scientific advances, technical innovations, organizational actions, and economic and political and strategic circumstances. Missing a single component in such a sequence, or delaying its introduction or effects because of some unforeseen events, results in very different outcomes and in lengthier transition periods. Once again, an excellent example illustrating this necessity of a specific sequence, and of assorted events delaying its progress, is provided by the recent emergence of LNG as a globally available fuel traded competitively on an intercontinental basis.

A long road toward this accomplishment had to include the invention and commercialization of gas liquefaction, establishment of LNG supply chain (liquefaction, tanker-borne transport, regasification), increase of typical liquefaction and LNG tankers' capacities in order to lower unit costs of the delivered gas, a greater number of importing countries in order to justify the construction and expansion of larger terminals, and extensive trunk and distribution pipelines in those importing countries that had previously no natural gas supply. And the process needed to create this new global industry was delayed by factors ranging from predictable (high capital costs of the first generation of LNG systems) to unforeseeable (OPEC-driven energy price increases, the Shah's fall and Khomeini's assumption of power in Iran, hydrocarbon price deregulation in the United States, concerns about early peak of oil extraction).

The road toward global LNG industry began in 1852 when the pioneering work done by James Prescott Joule and William Thomson (Lord Kelvin) on liquefaction of gases demonstrated that as a highly compressed air flows through a porous plug (a nozzle) it expands to the pressure of the ambient air and cools slightly (Almqvist, 2003). Repetition of this sequence creates a cooling cascade, the temperature of the gas expanded at the nozzle gradually declines and it eventually liquefies. Practical designs for commercial liquefaction of oxygen and nitrogen followed during the last three decades of the nineteenth century, with the most important contribution made by Carl von Linde (1842–1934), whose patented process (in 1895) combined the Thomson–Joule effect with what Linde termed countercurrent cooling, with compressed air expanded through a nozzle at the bottom of an insulated chamber used to pre-cool the incoming compressed air in a countercurrent cooler (Linde, 1916).

Because the United States was the only notable user of natural gas before World War II there was no commercial need for LNG: That is why Godfrey Cabot's patented handling and transporting liquid natural gas (Cabot, 1915) did not have any practical consequences. The first small LNG storage was built in West Virginia in 1939 and a larger one in Cleveland in 1941 to provide fuel for the periods of peak demand; in 1944 one of its tanks failed and the ignited vaporized gas killed 128 people in the plant's neighborhood. This accident used to be cited by those who wanted to portray LNG industry as very risky—but the investigation report concluded that the accident was caused by a poor tank design and that properly done the gas liquefaction and storage are not exceptionally dangerous (USBM, 1946).

Post–WWII surfeit of cheap crude oil and rapid expansion of North American gas extraction had postponed the beginning of the LNG era for another generation: The first demonstration shipment of LNG (from Lake Charles, LA to Canvey Island on the Thames) took place in 1959 with a tanker of just 5,000 m^3 (*Methane Pioneer*, a converted WWII Liberty class freighter). The first methane liquefaction plant was completed in Arzew, Algeria in 1964 and LNG exports to the United Kingdom began in the same year with two specifically designed tankers (*Methane Princess* and *Methane Progress*) of 27,400 m^3 each (Corkhill, 1975). They were followed by the Japanese imports from Alaska in 1969 and the French imports from Libya in 1970. But then the Groningen and the North Sea gas made the LNG imports uneconomical and when the Arzew–Canvey contract expired in 1979 it was not renewed.

Similarly, during the 1970s the United States built four regasification terminals for the import of Algerian gas (the first one in Everett, MA, in 1971) only to reduce their operation or to shut two of them down as the availability of domestic natural gas increased with the post-1993 wellhead price deregulation. This left Japan (with no domestic gas resources) as the world's leading importer of LNG, adding new long-term contracts for the gas from Abu Dhabi and Indonesia (in 1977), Malaysia (1983), and Australia (1989): By 1984 Japanese imports accounted for 75% of all LNG trade; by 1999 they were still 66% of the total. And while Taiwan (in 1990) and South Korea (in 1991) joined Japan as the other major Asian importers, the LNG trade remained confined by uncompetitive long-term contracts served by dedicated plants and ships along inflexible routes.

These realities were not conducive to any bold technical advances. For more than a generation, between the mid-1960s and the late 1990s, typical capacities of LNG trains (liquefaction units) remained at just 1–2 Mt/year, while the aggregate outputs of entire plants increased only gradually, from the pioneer Arzew's rate of 0.45 Mt/year in 1964 to 1 Mt/year in 1970, 1.5 Mt/year in 1980, 2.2 Mt/year in 1990, and 3.5 Mt/year in 2000. Some of these large-scale liquefiers have used the classic cascade cycle but most of them have relied on a mixed refrigerant cycle (using such gases as butane, propane, ethane, and nitrogen) devised by A. P. Kleemenko in 1960. And although the largest ship capacities increased fairly rapidly during the first decade of LNG trade—from 27,400 m^3 for the two pioneering ships in 1964 to 71,500 m^3 in 1969 and 126,227 m^3 in 1975—three decades later the dominant sizes (largely due to the Japanese restrictions on the maximum tonnage of LNG tankers) were still between 125,000 and 130,000 m^3.

Given a limited number of exporting countries (1 in 1964, 6 by 1980, 12 by 2000) and LNG tankers (fewer than 60 vessels until 1984, 100 by 1997), this slow capacity growth meant that the total LNG trade surpassed 50 Mt/year only by 1991 and that only in 1999 did it carry more than 5% of all exported gas (Castle, 2007). The industry began to change rapidly at the century's turn. Qatar joined the ranks of LNG exporters in 1997, in 1999 a new LNG plant in Trinidad and Tobago led to the reactivation of the two closed U.S. regasification plants (Elba Island in 2001, Cove Point in 2003), Nigeria and Oman began shipping LNG in 2000, followed by Egypt in 2005, Equatorial Guinea in 2007, and Russia (from Sakhalin) in 2009.

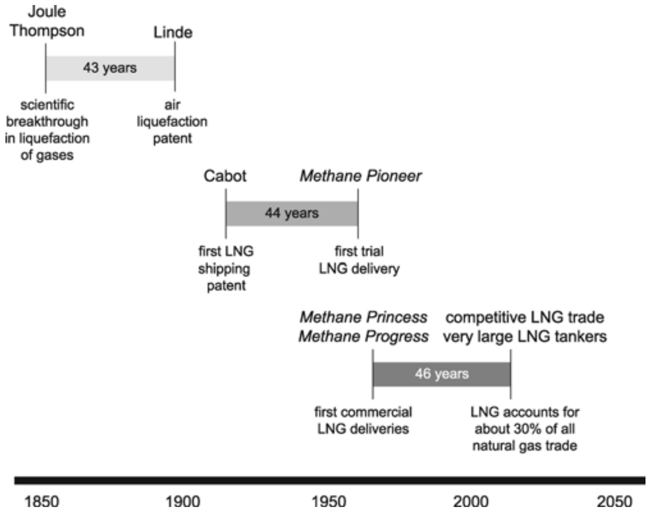
Increasing train size (maxima of 5 Mt/year by 2005, more than 8 Mt/year by 2008) and decreasing costs of train and tanker construction resulted in rapid capacity increases and bold plans for further expansion. Total export capacity rose from 100 Mt/year in 2000 to about 220 Mt/year by 2009. For three decades the standard LNG tanker design used large aluminum spheres (Kvaerner-Moss shells introduced in 1971) covered with insulation inside steel tanks and bolted to the vessel's hull. This design wastes storage space and steel spheres increase the ship's draft, making voluminous vessels impractical. In contrast, membrane design has insulated tanks of thin stainless steel shaped to fit the inner hull. As a result, average size of ships ordered in 2007 was about 180,000 m^3 and Qatargas has taken delivery of the first tankers belonging to new Q-Flex (210,000 m^3) and Q-Max (266,000 m^3) classes of ships. The company will eventually have 45 of these large vessels (Qatargas, 2009).

By 2008 there were 250 LNG tankers with the total capacity of 183 Mt/year and the global LNG trade carried about 25% of all internationally traded natural gas (BP, 2009). LNG was imported by 17 countries on four continents, and before the economic downturn of 2008 plans envisaged more than 300 LNG vessels by

2010 with the total capacity of about 250 Mt/year as the global LNG trade has moved toward a competitive market. LNG trade has been finally elevated from a marginal endeavor to an important component of global energy supply, and this has become true in terms of total exports (approaching 30% of all natural gas sold abroad) and number of countries involved (now more than 30 exporters and importers) as well as the flexibility of transactions (with a true market emerging).

This brief recounting of LNG history is an excellent illustration of the decades-long spans that are often required to convert theoretical concepts into technical possibilities and then to adapt these technical advances and diffuse them to create new energy industries (Figure 1.4). Theoretical foundations of the liquefaction of gases were laid down more than a century before the first commercial application; the key patent that turned the idea of liquefaction into a commonly used industrial process was granted in 1895, but at that time natural gas was a marginal fuel even in the United States (in 1900 it provided about 3.5% of the country's fossil fuel energy), and in global terms it had remained one until the 1960s, when its cleanliness and flexibility began to justify high price of its shipborne imports. Even then the first long-term contracts delivered gas only to affluent countries that could afford the price and that used most of the gas for shore-based electricity generation (Japan) or had preexisting trunk and distribution pipelines carrying domestically produced gas in place (United Kingdom, France, United States) that could be used to sell the imported gas to households and enterprises.

Figure 1.4 History of LNG shipments illustrates often very long time spans required for the maturation and diffusion of innovations in energy extraction, transport, and conversion.



Industry's subsequent growth was affected by a combination of events that could not have been predicted during the 1960s: by the two oil price crises of the 1970s, by the collapse of the Iranian monarchy in 1979, by the deregulation of U.S. natural gas prices (and the consequent boost of the domestic extraction), and by the collapse of the world oil price in 1985. As a result, many plans were postponed or cancelled. In 1975 it was expected that by 1981 Nigeria would begin its LNG exports to Europe, and Iran to Europe, the United States, and Japan (Faridany, 1975), but Nigerian exports began only nearly two decades later (in 1999) and Iranian shipments have yet to begin. The industry that began in 1964 moved only about 2% of all traded gas by 1980 and 5% of all natural gas exports only in 1999. At that time it was clearly an important earner for a few major exporters (Algeria, Indonesia, Brunei) and a significant source of fuel for the three leading importers (Japan, South Korea, Taiwan), but it still could not qualify as a key ingredient of the global primary energy supply.

If we take the years between 1999 (when worldwide LNG exports surpassed 5% of all natural gas sales) and 2007 (when the number of countries exporting and importing LNG surpassed 30, or more than 15% of all nations) as the onset of LNG's global importance, then it had taken about four decades to reach that point from the time of the first commercial shipment (1964), about five decades from the time that natural gas began to provide more than 10% of all fossil energies (during the early 1950s), more than a century since we acquired the technical means to liquefy large volumes of gases (by the mid-1890s)—and about 150 years since the discovery of the principle of gas liquefaction.

By 2007 it appeared that nothing could stop an emergence of a very substantial global LNG market. But then a sudden supply overhang that was created in 2008—and that was due to the combination of rapid capacity increases, lower demand caused by the global financial crisis, and the retreat of U.S. imports due to increased domestic output of unconventional gas—has, once again, slowed down global LNG prospects, and it may take years before the future course will become clear. In any case, the history of LNG remains a perfect example of the complexities and vagaries inherent in major energy transitions.

Chapter 2

GLOBAL TRANSITIONS: UNIVERSAL PATTERNS

The most obvious reality that emerges from the study of energy transitions done from the global perspective and across the entire historical time span is a highly skewed division of their progress: Stasis, stagnation, marginal adjustments, and slowly proceeding innovations marked the entire preindustrial era—while the process of industrialization and the evolution of postindustrial societies have been marked (indeed formed) by rapid, often truly precipitous diffusion of new inventions and widespread adoption of technical and organizational innovations. As a result, nearly five millennia of preindustrial history were almost completely dominated by reliance on inefficiently burned biomass fuels as the source of heat for households, metallurgy, and artisanal manufactures, and by exertions of human and animal muscles to provide nearly all requirements for mechanical energy (sails being the only early exception).

This situation did not change fundamentally even during the early modern era when some Western European societies began a small-scale extraction of coal (or peat) and when they adopted increasingly more efficient and more powerful water wheels and windmills. The two fundamental transitions, from biomass to fossil fuels and from animate to inanimate prime movers, have taken place only during the last few centuries (roughly three in the case of some European societies) or just a few recent decades (six in China's, four in India's case), and the emergence of electricity as the energy form of the highest quality began only during the 1880s. Inevitably, these transitions began on small local scales, evolved into nationwide developments, and eventually became truly global phenomena. Only the earliest innovators were able to maintain their advantage for a period of time, while the more recent advances have been diffusing with only a minimum lag (a phenomenon perhaps best illustrated by China's rapid post-1980 modernization).

I will trace all of these developments by following first the grand fuel sequence of millennia-long dependence on biomass energies that was replaced by now virtually universal dependence on fossil fuels. In the next section I will emphasize importance of electricity in modern societies and review the development of thermal, hydro, and nuclear generation. Then I will offer a brief history of a critical transition from animate to mechanical prime movers, and the chapter will conclude with the best possible quantitative appraisal of these trends on the global scale—and with inevitable caveats regarding the quality of various historical data used for these analyses.

GRAND FUEL SEQUENCE: FROM BIOMASS TO COAL AND HYDROCARBONS

All preindustrial societies had a rather simple and persistent pattern of primary fuel use as they derived all of their limited heat requirements from burning biomass fuels. Fuelwood (firewood) was the dominant source of primary energy, but woody phytomass would be a better term: the earliest users did not have any requisite saws and axes to cut and split tree trunks, and those tools remained beyond the reach of the poorest peasants even during the early modern era. Any woody phytomass was used, including branches fallen to the ground or broken off small trees, twigs, and small shrubs. In large parts of the sub-Saharan Africa and in many regions of Asia and Latin America this woody phytomass, collected mostly by women and children, continues to be the only accessible and affordable form of fuel for cooking and water and house heating for the poorest rural families.

Moreover, in some environments large shares of all woody matter were always gathered by families outside forests from small tree clumps and bushes, from the litter fall under plantation tree crops (rubber, coconut) or from roadside, backyard, or living fence trees and shrubs. This reliance on non-forest phytomass also continues today in many tropical and subtropical countries: Rural surveys conducted during the late 1990s in Bangladesh, Pakistan, and Sri Lanka found that this non-forest fuelwood accounted for more than 80% of all wood by households (RWEDP, 1997). And in less hospitable, arid or deforested, environments, children and women collected any available non-woody cellulosic phytomass, fallen leaves (commonly raked in North China's groves, leaving the ground barren), dry grasses, and plant roots. For hundreds of millions of people the grand energy transition traced in this chapter is yet to unfold: They continue to live in the wooden era, perpetuating the fuel usage that began in prehistory.

Another usage that has been around for millennia is the burning of crop residues (mostly cereal and leguminous straws, but also corn or cotton stalks and even some plant roots) and sundry food-processing wastes (ranging from almond shells to date kernels) in many desert, deforested, or heavily cultivated regions. And on the lowest rung of the reliance on biomass fuels was (and is) dry dung, gathered by those with no access to other fuels (be it the westward-moving settlers of the United States during the nineteenth century collecting buffalo dung or the poorest segments of rural population in today's India) or whose environment (grasslands or high mountain regions) provides no suitable phytomass to collect (Tibetan and Andean plateaus and subtropical deserts of the Old World where, respectively, yak, llama, and camel dung can be collected).

But besides constancy there have been also important changes in wood use and production. Charcoal, produced from a variety of wood species (hardwoods as well as conifers; see Figure 1.1), was widely used in antiquity and it eventually became a preferred source of heat for those who could afford its higher price and valued its smokeless combustion. Remarkably, the British House of Commons was heated by charcoal until 1791, long after (as I will soon explain) everybody in cities, including the royal family, switched to coal. Charcoal was also the best choice for many small manufactures, particularly for metalworking. But this cleaner fuel was produced so inefficiently that in mass terms up to 15 units of wood were need for a unit of charcoal, and even with a lower, typical preindustrial mean of 5:1 this conversion entailed about 60% loss of initially charged energy content (air-dry wood has about 15 GJ/t and density of 0.65 t/m^3 while charcoal's energy density is 29.7 GJ/t).

And in households the universal reliance on phytomass combustion had evolved from using inefficient open hearths to burning wood in stoves with proper chimneys. These stoves were a surprisingly late innovation, beginning with tiled *Kachelofen* (common in Central Europe by the sixteenth century), and with various iron stove designs introduced during the eighteenth century (including the famous but misleadingly named Franklin stove in 1742: it was actually just an iron-lined fireplace). At the same time industries introduced more efficient, larger furnaces and steam-generating boilers, and iron makers began to convert wood to charcoal on a massive scale needed to feed larger blast furnaces. As a result, growing cities, expanding manufactures, and increasing iron production led to the demise of surrounding forests, and affordable availability of nearby wood or charcoal supplies (as long-distance land transport using pack or draft animals was usually prohibitively expensive) became a key factor limiting the size of preindustrial cities and the level of iron output.

Unfortunately, we have no reliable records of ancient or medieval household biomass fuel consumption, and even for the early modern era and the eighteenth and nineteenth centuries there is only some highly fragmentary information from a few countries. The United States, with some fuelwood data going back to the seventeenth century, is perhaps the most important exception. And, of course, in some regions household use was easily equalled or surpassed by industrial demand of iron- or glassmaking or for salt production. German medieval glassmaking was particularly wood-intensive, with as much as 2.4 t of wood (97% of it burned to obtain potassium rather than energy) used per kg of glass, an equivalent of 90 MJ/kg (Sieferle, 2001). Salt works using large heated pans to evaporate brines produced (depending on salt concentration) 15–100 kg of salt/m^3 wood, demanding as much as 500–600 MJ/kg.

And reliable information on English iron smelting indicates that up to 20 kg (almost 600 MJ) of charcoal were used to produce 1 kg of hot metal during the Middle Ages and about 8 kg (240 MJ) of charcoal were needed for 1 kg of iron by the end of the eighteenth century (Smil, 1994). This demand led to extensive deforestation, a transformation that undercut not only the viability of charcoal-using establishments but also the very existence of nearby villages and cities that needed wood as timber for their houses and as raw material for making nearly all of their machines, devices, and utensils of daily life. At the same time, a more predictable supply of wood was secured in some regions by deliberate planting of trees in backyards, on roadsides, on otherwise infertile slope land, or in fuelwood groves to supply nearby farms or villages.

Classical cases of energy transition from biofuels to fossil fuels (both in the sense of being the most consequential for the subsequent economic advancement and the best studied from historical and technical perspectives) involve gradual shifts from total reliance on fuelwood and charcoal to increasing uses of coal, in both domestic and industrial settings. But that sequence, best known from developments in England, Germany, or the United States, has not been a universal phenomenon. As I will describe in the next chapter when detailing several prominent energy transitions on the national level, there was an interesting early exception when the Golden Age of the Dutch Republic (1608–1672) was energized by a unique shift from biofuels to peat, the youngest of all fossil fuels, aided considerably by a widespread use of wind power (de Zeeuw, 1978; Unger, 1984).

And during the twentieth century many Asian and African countries with abundant hydrocarbon resources but with no domestic coal deposits moved from the biofuel era directly to the use of refined oil products and natural gas, with some desert countries moving from very low per capita consumption rates of biomass fuels to some of the world's highest per capita rates of hydrocarbon use in just two generations. But, without exception, all of the world's major economies—the United States, the United Kingdom, Germany, France, Russia, Japan, China, and India—had followed the classical sequence from biofuels to coal, and that is why this transition should receive the closest attention.

During the earliest stage of small-scale local coal extraction there was no need to discover the fuel and to develop elaborate mines: The first seams to be tapped were those outcropping to the surface or those under only a shallow overburden and accessible by open pits or short shafts. In some places and at different times—ranging from the Roman Britain of the first two centuries CE to Arizona Hopis of the thirteenth century—coal was used locally for heating, and its first metallurgical uses were during the Han dynasty, where the fuel was packed around iron ore-filled crucibles (Needham, 1964). The oldest European extraction is documented in Belgium in 1113 and London received its first coal deliveries in 1228 but, as Nef (1932) noted, until the sixteenth century the fuel was regularly burned only by poor households who could not afford to buy wood and lived close to coal outcrops.

The genesis of the growing British reliance on coal offers some valuable generic lessons. Thanks to Nef's (1932) influential work a national wood crisis has been commonly seen as the key reason for the expansion of coal mining between 1550 and 1680—but other historians could not support this claim, pointing to the persistence of large wooded areas in the country, seeing such shortages as largely local and criticizing unwarranted generalization based on the worst-case urban situations (Coleman, 1977). This was undoubtedly true, but not entirely relevant, as transportation constraints would not allow the emergence of a national fuelwood market, and local and regional wood scarcities were real.

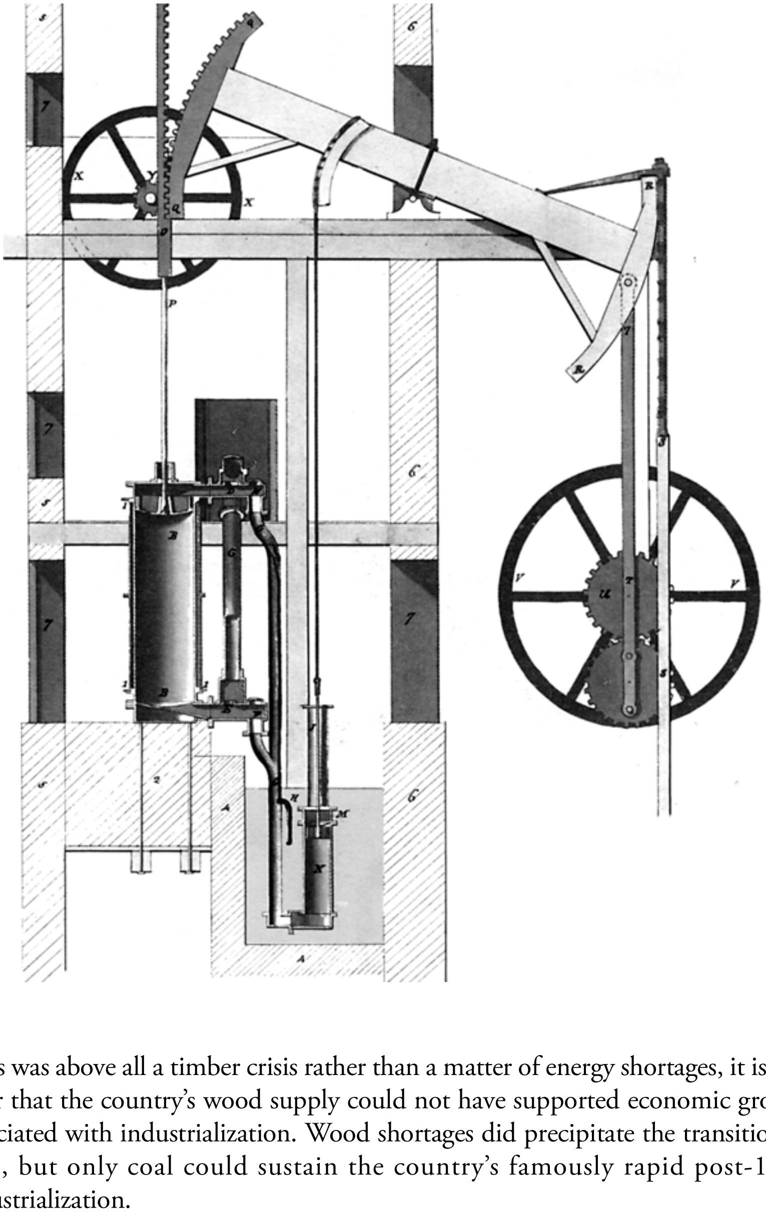
At the same time, the best available reconstruction of energy prices in the southeast of England shows that (in real terms) fuelwood prices were actually fairly stable between 1550 and 1650 and that it was a steady decline in coal prices that primed the expanding fuel extraction (Fouquet, 2008). By 1600 coal prices were about half that of wood prices when compared per unit of gross energy, and by the time wood prices began to rise during the latter half of the seventeenth century (driven not only by growing industries but also by expanded shipbuilding), coal was the dominant source of energy for nearly all British industries (with a major exception of iron smelting dependent on charcoal) as well as for household heating (Hatcher, 1993). Coal production was greatly boosted with the invention of steam engine and with the spreading replacement of charcoal by coke in iron smelting.

Again, neither of these innovations was immediately successful. Thomas Newcomen's highly inefficient steam engine was introduced by 1712, but even its improved version had a limited impact (it was widely used only by coal mines), and it was only the machine's radical redesign patented in 1769 by James Watt that gained wider commercial acceptance during the last three decades of the eighteenth century (Figure 2.1; for more details, see the third section of this chapter). Expanded coal extraction created its own positive production feedbacks, as deeper shafts sank far below local water tables and required frequent or constant pumping, and as deeper mines also needed more energy for ventilation and for hoisting of the fuel.

Britain was circumventing its early eighteenth-century local charcoal shortages by iron imports from Sweden and by lowering the rate of charcoal use in smelting. Coke was successfully used in iron smelting by Abraham Darby in 1709, but it was too costly (because of its inefficient production) and its widespread acceptance came only after 1750 (Harris, 1988). Coke, much less friable than charcoal, made it possible to build taller, more voluminous blast furnaces and due to its higher temperature of combustion it also produced better iron. By 1800 Britain was extracting about 9 Mt of coal a year while U.S. production was only about 100,000 t, most of it coming from Pennsylvania (both bituminous coal and anthracite) with smaller contributions from Virginia, West Virginia, and eastern Kentucky (Milici, 2003).

Before 1800, major coal-mining regions were also emerging in continental Europe in northern France, around Liège in Belgium, in Bohemia, and in Silesia, Saxony, and the Ruhr region of Germany. German transition to coal is a notable example of the fact that the shift from wood to coal did not have to be primed by increasing shortages of fuelwood (Sieferle, 2001). Large parts of the country were always well forested, and even by the end of the eighteenth century it was possible to secure enough fuelwood at acceptable prices. While the German wood

Figure 2.1 Cross-section of Watt's engine. Reproduced from Farey (1827).



crisis was above all a timber crisis rather than a matter of energy shortages, it is also clear that the country's wood supply could not have supported economic growth associated with industrialization. Wood shortages did precipitate the transition to coal, but only coal could sustain the country's famously rapid post-1870 industrialization.

Timber shortage could be best addressed by improved forestry practices and by reserving more wood harvests for timber. These measures led to state-promoted, even state-subsidized switch to coal, first in some state-owned industries and later in households. And it was only because of this switch that, as Sieferle (2001, p. 180) put it, "the limits of the agrarian solar energy system were burst in the transition to fossil energy system. Precisely this constituted the solution that formed the energy basis for the industrial transformation and marked it as a unique epochal discontinuity." This conclusion has, of course, a universal validity.

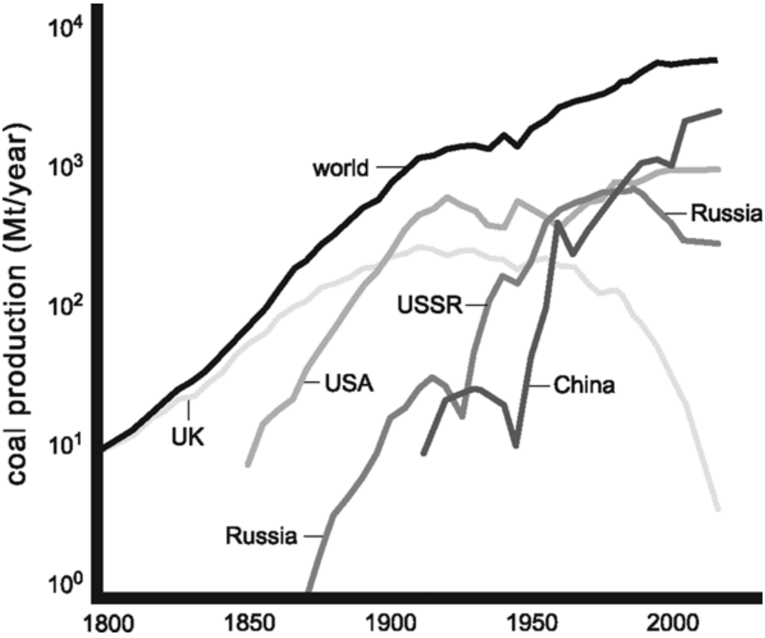
Because bituminous coals of acceptable quality, and even more so the poorer lignites, are widely distributed, it was not long before scores of countries—including Sweden, Greece, and Spain in Europe, China, India, Japan, and Turkey in Asia, and Mexico and Peru in Latin America—began producing the fuel on larger scale, but Britain maintained its coal-mining lead almost until the century's end. In 1800 the country produced more than 80% of the global output and by 1870 its share was still 50%. But by 1899 it was surpassed by the U.S. extraction, and Germany's production was not far behind the British extraction (but more than a quarter of that country's coal was low-energy lignite). France, the Austro-Hungarian Empire, Belgium, Russia, and China were the other major producers at the beginning of the twentieth century when coal became firmly established as the single most important primary fuel, having surpassed fuelwood and charcoal sometime during the 1890s.

Three grand trends marked the global coal production of the twentieth century: continuous decline of its relative importance, continuous growth of its absolute contribution to the worldwide total of primary energies, and the transformation from a highly labor-intensive to a highly mechanized industry. In 1900 global extraction of hydrocarbons was only marginally important; by 2000 they far surpassed coal's contribution. In 1900 the worldwide extraction of bituminous coals and lignites added up to about 800 Mt; a century later it was about 4.5 Gt, a roughly 5.6-fold increase in mass terms and (because of the declining energy density of extracted coal) almost exactly four-fold increase in energy terms. Much as fuelwood energized the early stages of eighteenth- and nineteenth-century industrialization, coal energized the building of modern industries and infrastructures in all European countries as well as in North America, Australia, and Japan during the first half of the twentieth century, and the fuel continues to play a critical role not only in China and India but also in the United States and Europe because of its contribution to electricity generation.

After 1950 high levels of mechanized underground mining were the norm (except in China's small mines), easily doubling or tripling typical pre–WWI labor productivities. Even greater productivities (and much higher safety) have been achieved by extracting an increasing share of the fuel by surface (open-cast) mining. And the worldwide coal industry of 2000 differed from its predecessor of 1900 also because of its profoundly changed spatial distribution. Perhaps the most notable national trends include the near demise of British extraction, ascent of the Soviet and then the retreat of the Russian output, continuing high levels of U.S. production, huge increase of China's extraction, and the emergence of new large coal exporters, Australia and Indonesia.

The British output peaked in 1913 (287 Mt from more than 3,000 mines), and it was still above 200 Mt during the 1950s (Hicks & Allen, 1999; Figure 2.2).

Figure 2.2 Coal production, 1810–2010. Plotted from data in UNO (1956 and 1976), Etemad et al. (1991), and BP (2009).



But the subsequent oil imports and then the domestic production of crude oil and natural gas from the North Sea reduced it to less than 100 Mt during the 1980s and by 2000 the United Kingdom was extracting less than 20 Mt/year and it became an importer of coal, joining such larger buyers as Japan, South Korea, Taiwan, and India. Most of those imports came from the new coal-exporting powers, Australia, Indonesia, South Africa, and Colombia and from Russia and the United States.

The United State's 1900 extraction doubled by 1913 and it reached the pre–WWII peak of nearly 600 Mt in 1923; that total was surpassed again only during 1944 in the midst of wartime effort, and after another post-war pullback the industry became the prime energizer of rapidly expanding electricity generation, a period that lasted until the early 1970s. By that time the USSR was the world's second-largest producer (having surpassed the United Kingdom in terms of total energy content already by 1950), with China rising fast. But the United States yielded to China only in 1991, and by 2005 the gap between the two largest coal producers was more than twofold in mass terms and about 1.8-fold in terms of coal's total energy content (Figure 2.2).

As in coal's case, it is impossible to date the earliest instance of human familiarity with crude oil because in some locales the fuel was known for millennia. As any liquid under pressure, crude oil has the propensity to seep to the surface along fracture zones and to form black lakes of tar or bitumen pools and even, when under high pressure and mixed with natural gas, to create periodically reappearing burning pillars. And as in coal's case, the fuel was used in small amounts, often for non-energy applications, since antiquity. In ancient Mesopotamia asphalts and bitumens were used in floor and wall mosaics and as protective coatings and lighter oils were burned in fire pans for illumination; such uses could be subsequently copied by the Greeks and the Romans and later they were perpetuated by the inhabitants of the medieval Middle East (Forbes, 1964).

Oil from natural seeps in western Pennsylvania was collected during the late eighteenth century and bottled to be sold as a medicinal "Seneca oil," and crude oil, although not in its liquid form, was also known in preindustrial Europe in the form of oil sands in Merkwiller-Pechelbronn in Alsace where the first shallow (9.75-m) pit was dug in 1745, the first refinery was built in 1857, water injection began in 1879, and small-scale production continued until 1970 (Walther, 2007). There was only one locality in the preindustrial world where active steps were taken to collect crude oil, the Absheron peninsula of the Baku region on the Caspian Sea in Azerbaijan. Baku's oil pools and wells were described by medieval Arabic travelers and historians, and in 1593 an inscription was affixed near a 35-m deep well that was dug manually in Balakhani (Mir-Babaev, 2004).

By the time Czarist Russia took over Baku (in 1806) the Absheron region had many shallow wells from which lighter oil was collected in order to produce kerosene (by thermal distillation) and use it for local lighting as well as for export by camels (carried in skins) and in wooden barrels on small ships. In 1837 Russians built the first commercial oil-distilling factory in Balakhani and nine years later they sank the world's first (21-m deep) exploratory oil well in Bibi-Heybat and thus opened up what was later classified as the world's first giant oilfield (i.e., one having at least 500 million barrels of recoverable crude oil). Baku was thus the place where the modern oil era began, and 1846 was its beginning.

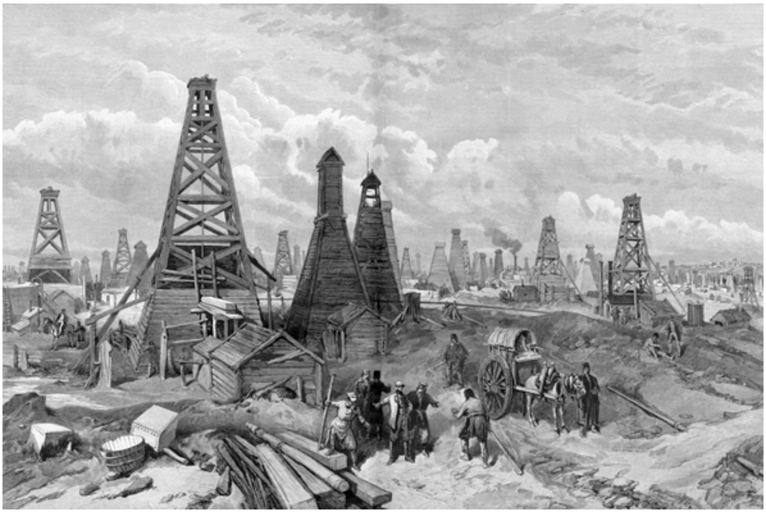
North American developments followed soon afterwards, spurred by the search for an alternative source of lighting to replace whale oil (Brantly, 1971). In 1858 Charles Tripp and James Miller Williams financed America's first (manually dug) oil well near Black Creek (Lambton County in southwestern Ontario) and a year later, amidst the world's first oil boom, the hamlet was renamed Oil Springs. And 1859 was also the year of the first commercial U.S. oil discovery as Edwin Drake (employed by George Bissell, who started the Pennsylvania Rock Oil Company) supervised the drilling of a shallow well at an oil seep site at Oil Creek near Titusville, Pennsylvania. The well (whose drilling used an ancient Chinese percussion method, but powered by steam engine) struck oil at the depth of 21 m on August 27, 1859, the date the Americans use as the beginning of the modern oil era.

During the early 1860s crude oil thus began to figure on the balance sheets of primary energy consumption in Russia, Canada, and the United States. Canada soon fell out of the new oil league: Another Oil Springs boom began in 1862 with the world's first gusher, and in 1865 oil was discovered also in nearby Petrolea, but the pressure in Ontario's small reservoirs soon declined, steam pumps were used to produce diminishing volumes, and by the 1890s a shrinking industry could not compete with much cheaper American oil. Canada's second oil era began only with the post–WWII discoveries in Alberta.

Russian oil extraction also progressed swiftly thanks to substantial foreign investment (above all by Ludwig and Robert Nobel, who launched Nobel Brothers Petroleum Company in 1875, and the Rothschild brothers who established the Caspian and Black Sea Oil Industry and Trade Society in 1883) and to new major discoveries at the giant Bibi-Heybat field in 1878 (Figure 2.3). The only other notable pre-1900 crude oil developments took place in Romania, Indonesia, and Burma. In Romania pools and shallow wells were known for centuries and the first commercial refinery was opened in Ploieşti (60 km north of Bucharest) in 1857, and the country's only giant oilfield was discovered in 1900.

Oil was discovered in northern Sumatra in 1883 and the Burmese production began in 1887. Most of this Asian oil was shipped to Europe, where coal was generally at the peak of its dominance and crude oil amounted to only a minuscule addition to the total primary energy supply. Before World War I also came the first major oil discoveries in the Middle East (on May 26, 1908, Masjid-e-Soleiman in Iran), Mexico, and Venezuela (the giant Mene Grande field on Lake Maracaibo's coast in 1914). With the exception of pre–WWI discoveries in Iran, all major finds in the Persian Gulf region came only between the late 1920s and the early 1960s. Iraqi Kirkuk was first (discovered in 1927, producing since 1934), followed

Figure 2.3 Baku oil wells. Reproduced from *The Illustrated London News*, June 19, 1886, 9, 671.



by Iranian Gachsaran and Haft Kel in 1928, Naft-i-Said in 1935, Pazaran in 1937, and Agha Jari in 1938.

In that year came also the first large discovery in Kuwait, and in Saudi Arabia (Dammam on the western shore of the Persian Gulf near Dhahrān), followed by Abqaiq and Abu Hadrīya in 1940, Qatīf in 1945, and in 1948 al-Ghawār (southwest of Dhahrān), that was confirmed by 1956 to be by far the world's largest reservoir of crude oil. Canada also rejoined the ranks of major oil countries with the discoveries of giant oilfields in Alberta (Leduc-Woodland in 1947 and Redwater in 1948) and the Soviet center of oil production shifted from Baku to the Volga-Ural region, where the first strike in 1937 (giant Tuymazy) was followed by two more giants in 1945 and 1948 (Mukhanovo and Romashkino).

Postwar recovery in Europe, the USSR, and Japan and the U.S. baby boom–driven economy stimulated demand for oil, as did the twin trend of rising car ownership and shift to suburbs, soon joined by the jet-powered air travel. Increasing networks of large-diameter pipelines and construction of massive crude oil supertankers made it possible to export the fuel at a very low cost, and general adoption of efficient catalytic cracking enabled production of larger volumes of the most valuable transportation fuels, gasoline, kerosene, and diesel oil. Low oil prices also accelerated the transition from biofuels and coals in a number of Asian and Latin American countries.

Future of this increased supply seemed to be secure, as the 1950s and 1960s were the two record decades for the discovery of giant oilfields. These finds included giants in Saudi Arabia (Safānīya-Khafjī, Manīfa, Berri, Shayba), Iraq (Rumaila), Iran (Ahwaz, Marun, Fereidūn), and Abu Dhabi (Bū Hasa, Zākūm, Asab), as well as in Canada (Pembina, Weyburn-Midale, Swan Hills) and the United States (the Prudhoe Bay on the North Slope of Alaska in 1968) and the largest Soviet supergiant in Western Siberia (Samotlor in 1965). Discoveries in Algeria, Libya, and Nigeria made Africa into a major new supplier and a supergiant Daqing oilfield in Heilongjiang (discovered in 1959) finally changed China's meager oil fortunes.

Size of the Middle Eastern oilfields and ready availability of Western (and later also Japanese) investments brought rapid extraction increases: For example, the Saudi output (all of it managed by the Arabian American Oil Company) tripled between 1960 and 1970 (from 62 to 192 Mt/year), while the Kuwaiti output went from less than 1 Mt in 1945 to more than 80 Mt by 1960. Dissatisfaction with low oil prices led to the establishment of the Organization of Petroleum Exporting Countries (OPEC) in 1960. As the oil demand continued to rise while the U.S. production began to fall in 1971 (it remained the world's largest until 1975), OPEC began raising its prices. Its first round of large increases in 1973–1974 was followed by the second round in 1979–1981 that was precipitated by the overthrow of the Iranian monarchy.

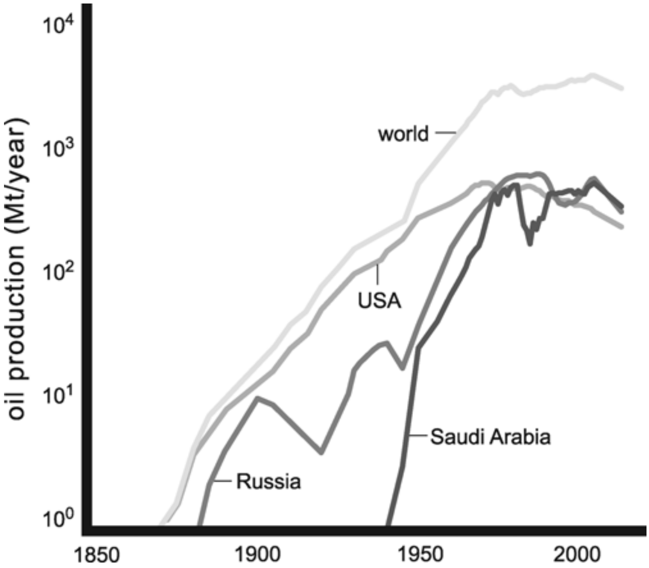
At the same, discoveries of giant oilfields were declining, but they included Mexico's Cantarell Complex in 1976 and the three largest fields in the North

Sea's Norwegian waters (Ekofisk in 1971, Statfjord in 1974, and Gullfaks in 1978). Concerns arose about the adequacy of the future supply but OPEC overplayed its hand and as the oil price rose to nearly $40/bbl, the global demand (and with it the worries about an imminent peak oil production, as well as new drilling) receded. Global oil production peaked at just over 3.2 Gt in 1979 and it did not surpass that level until 1994 (Figure 2.4). Prices remained fairly stable until the century's end, and new major discoveries of the 1990s came from Mexico, Iran, Brazil, and from the U.S. offshore waters in the Gulf of Mexico (Ursa in 1991, Auger in 1996, and Alpine and Thunder Horse in 1999).

Meanwhile another major change took place, as the USSR, the world's largest oil producer since 1975, dissolved, and the aggregate oil extraction of its former states declined by nearly a third between 1991 and 1996, making Saudi Arabia a new leader starting in 1993. Prices remained low and fairly steady and total extraction increased modestly during the first five years of the new millennium. Subsequent combination of a weaker U.S. dollar (all international oil trade is denominated in US$), speculation in commodity futures, and rising demand in China and India pushed them to new nominal (and demand-destroying) highs of nearly $150/bbl in July 2008 before they receded, and later somewhat rebounded. As a result, crude oil's share of the global primary fuel supply has been declining while the shares of coal and natural gas have been rising.

Natural gas is actually a mixture of light combustible hydrocarbons, with methane dominant but with up to a fifth of the volume made up of ethane,

Figure 2.4 Crude oil production, 1850–2010. Plotted from data in UNO (1956 and 1976), Etemad et al. (1991), and BP (2009).



propane, and butane; other gases commonly present include CO_2, H_2S, N_2, and water vapor. Because of its natural seeps the gas was also known in some regions in antiquity and its first well-documented commercial use dates to the Han dynasty (200 BCE), when wells were drilled with percussion tools and the gas was led through bamboo tubing to burn under large iron pans and evaporate brines to produce salt in the landlocked Sichuan province (Needham, 1964). Americans were the industry's modern pioneers, with the first shallow natural gas well dug in 1821 in Fredonia, New York, by William Hart. Rising volumes of the gas became available with the expanding crude oil production (associated gas, mixed with or dissolved in the liquid fuel) but in the absence of long-distance pipelines some of the fuel was used for local lighting but most of it was wasted (set alight and flared).

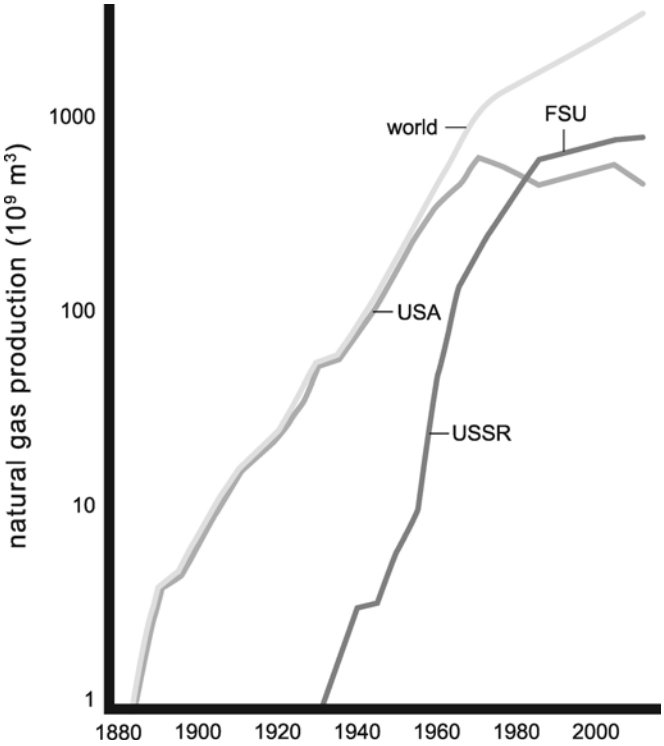
Moreover, in the cities natural gas faced a long-established competition by the gas made from coal (town gas, first produced in London in 1812; in the United States, in Baltimore, in 1816), and by the 1880s gaslights began to be replaced by new electric lights. Three innovations had to take place before natural gas could become a major household and industrial fuel: commercialization of a safe burner mixing the gas and air in correct proportion to produce a safe flame for cooking and heating; introduction of large-diameter, high-pressure pipelines that could carry greater volumes of the gas over longer distances; and efficient compressors to propel the gas through pipes. The first advance began with Robert Bunsen's burner in 1885 and it was perfected by temperature-regulating thermostats that could be used to monitor and regulate the flame as needed.

Better pipes and pipeline construction method began to diffuse during the 1930s, but it was only after World War II when metallurgical advances and better welding and pipe-laying techniques brought a pipeline construction boom (with trunk lines having diameters up to 120 cm), first in the United States, and by the 1960s also in Europe and parts of Asia. Another important post–WWII advance was the replacement of reciprocating engines or electric motors used in centrifugal compressors that pressurize the transported gas (and spaced in intervals of 60–160 km along the pipeline) by inherently more efficient gas turbines which could be powered by consuming a small amount of the transported gas. These technical constraints were the main reason why—with the exception of the United States, where natural gas extraction rose to more than 10% of all fuel production by 1940—the gas industry became an important global presence only after World War II.

Clean combustion and flexible use made natural gas a much sought-after fuel, used not only for space heating and cooking but also in numerous industrial processes as well as to generate electricity (either by producing steam in thermal plant boilers or by powering gas turbines). Moreover, natural gas has also outstanding non-energy roles as an excellent feedstock for production of ammonia and a wide variety of synthetic materials. Not surprisingly, its global extraction expanded rapidly, from about 200 Gm^3 in 1950 to 1.2 Tm^3 by 1975 and 2.4 Tm^3 in 2000, a 12-fold rise in 50 years. The United States remained the world's largest natural gas producer until 1982, when it was surpassed by the USSR: Ever since, the flow from the supergiant fields in Western Siberia has kept Russia as the world's largest producer and exporter of natural gas (Figure 2.5).

Canada has been the world's third-largest producer since the late 1950s and discoveries in the North Sea made the United Kingdom the fourth-largest producer. Algeria, Indonesia, Iran, the Netherlands, Uzbekistan, Kazakhstan, and Norway made up the rest of the global top ten in 2000. Growing LNG trade—by 2009 15 countries, led by Qatar and followed by Malaysia, Indonesia, Algeria, Nigeria, Australia, and Trinidad and Tobago were exporting LNG and Japan, South Korea, Spain, the United States, Taiwan, and France were the main buyers—means that much less gas is now wasted, but in 2005 the share of flared gas, at about 4% of the global output, was still equal to nearly half of Russia's large exports (Mouton, 2005). Gas-flaring sites in Russia, Iraq, Iran, and Nigeria can be seen on nighttime satellite images as the brightest spots on the Earth's surface.

Figure 2.5 Natural gas production, 1880–2010. Plotted from data in UNO (1956 and 1976) and BP (2009).



A NEW QUALITY: GENERATION OF ELECTRICITY

There are many reasons why electricity has become the preferred form of energy and why it is, in many ways, absolutely essential for the normal functioning of modern civilization. Electricity's use results in economic benefits unsurpassed by any fuel, as it offers superior final conversion efficiencies, unmatched productivity, and unequaled flexibility, with uses ranging from lighting to space heating, from metallurgical to food industries, and from any stationary to all but one mobile use (commercial flight). Its other much-appreciated advantages include precise control of delivery (ranging from less than one watt for the most efficient microchips to multigigawatt flows in large national or regional grids), focused applications on any conceivable scale (from micromachining to powering the world's largest excavators and the world's fastest trains), and, of course, no need for storage and the ease of using (flipping the switch) energy that is noiseless and, at the point of conversion, absolutely clean.

And with the now universal reliance on electronic monitoring and automation (be they in incubators or nuclear reactors, rapid trains or large banks) electricity's role as the controller, regulator, and enabler of materials and information flows became even more fundamental: Only a small share of its generation energizes these controls—for example, the best calculations show that servers, modems, and routers consume about 3% of all U.S. electricity (Koomey, 2007) and that the Internet claims about 5% of the global electricity use (Sarokin, 2007)—but cessation of that supply would have profound effects on modern societies.

Most of the world's electricity is generated by the burning of fossil fuels: In 2005 that share was almost exactly two-thirds, with coal accounting for more than 60% of the latter fraction, or just over 40% of the global total (WCI, 2009). Hydroelectricity came next with about 17%, followed by nuclear electricity (just over 15%); despite their recent rapid expansion, all forms of new renewable electricity generation supplied only about 2% of the 2005 total, with most of it coming from wind turbines: In 2008, after doubling the 2005 installed capacity, their share was 1.5% of the global total (WWEA, 2009). Geothermal plants were the second-largest renewable contributor and photovoltaic (PV) conversion generated a minuscule share of less than 0.1%. Moving away from the reliance on fossil fuels in general (and from coal combustion in particular) would necessitate a massive reshaping of the industry.

Anything beyond a marginal (less than 10% share) shift to generation based on renewable energy flows would affect the key infrastructural arrangements of the industry (location, size, and load factors of its generating capacities and high voltage (HV) transmission links among the primary concentrations of new supply and major load centers). Alternatively, any bold moves toward a system based largely on nuclear generation would have to overcome a number of recalcitrant socioeconomic and technical obstacles (with the post-1970s record giving little encouragement that this could be done expeditiously). And, not to forget recently fashionable talk of carbon sequestration and storage, retaining the industry's coal base but hiding its CO_2 emissions underground would require putting in place a new massive industry whose mass-handling capacity would have to rival that of the world's oil industry even if the controls were limited to a fraction of the generated gas.

And it would not matter if the shift toward renewables were to be motivated primarily by diminishing fossil fuel supplies obtainable at reasonable cost—as indicated by recent concerns about an imminent peak of oil production (Deffeyes, 2004; Goodstein, 2005), about exaggerated claims of coal reserves (Rutledge, 2008) or about declining energy returns on investment (Hall & Day, 2009)—or if it were a result of a deliberate decision undertaken to prevent what is now increasingly seen as intolerable climate change, that is anything with average global tropospheric temperature more than 2°C above the preindustrial mean. I will return to all of these considerations in the book's last chapter; here I will outline, as in the previous section where I traced the rise of fossil fuels, some of the milestones on the road to modern electrified societies.

Some electric phenomena (most notably static electricity) were known for centuries, and experimental foundations of modern science of electricity were laid before 1850. Alessandro Volta (1745–1827) built the first battery in 1800 (the unit of electromotive force bears his name), Hans Christian Ørsted (1777–1851) discovered the magnetic effect of electric currents in 1819 (the unit of magnetic field strength is named after him), André-Marie Ampère (1775–1836) formulated the concept of a complete circuit and quantified the magnetic effects of electric currents (the unit of electric current has his name), and in 1831 Michael Faraday (1791–1867) discovered the induction of electric current in a moving magnetic field, the finding that was eventually translated into large-scale conversion of mechanical energy into electricity without bulky and heavy batteries able to deliver only limited power (farad is the unit of electrical capacitance).

But it was only during the 1880s when this new form of energy became commercially available, with the first electricity-generating plants serving only areas encompassing a few city blocks. Until that time fuels were the only, albeit very diverse, category of primary energies whose conversions could be used to heat rooms, cook food, generate mechanical energy for industrial processes or for transportation, and produce light, or be transformed into secondary fuels of all three states (charcoal, gasoline, town gas) that could have the same final uses. Remarkably, electricity's commercial introduction was not an outcome of a gradual accumulation of diverse developments but a matter of deliberate creation of an entire new energy system by a boldly thinking individual in one location.

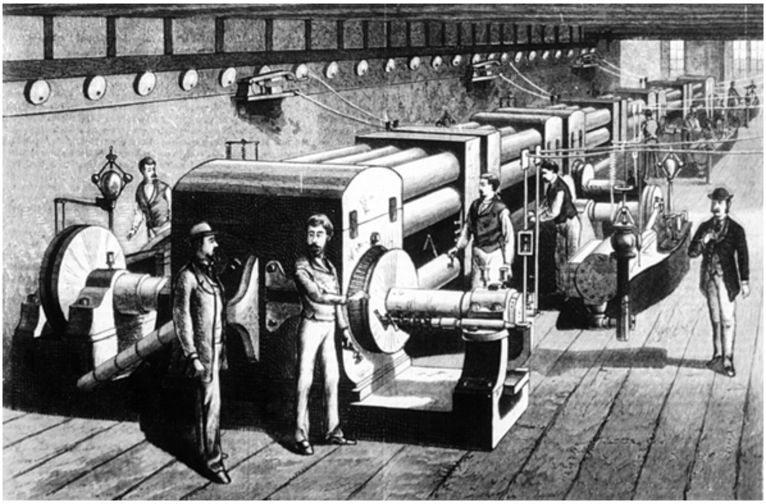
Edison's epochal designs and the first practical applications of a complete electricity system—including generation, transmission, distribution, and final conversion—took place shortly after his invention of the first practical light bulb, patented in 1879. His first commercial systems, the short-lived Holborn

Viaduct in London in 1881 (it closed in 1884) and Pearl Street Station in New York (powered up in September 1882) derived the kinetic power needed to rotate their dynamos from the combustion of coal and from the reciprocating motion of steam engines and therefore produced electricity as a form of secondary energy. Pearl Street Station had four coal-fired Babcock & Wilcox boilers (about 180 kW each) located on the ground floor, and six Porter-Allen steam engines (94 kW) directly connected to Jumbo dynamos on the reinforced second floor and by the end of the year, after adding three more dynamos, it was supplying electricity for 5,000 light bulbs (Figure 2.6).

Generation of primary electricity, that is, production of electric current without any fuel combustion, began at the same time. The first small American system based on water power was put in operation in the same month (September 1882) as the Manhattan station, and the first English hydro station began to generate electricity already a year earlier, in September 1881. Edison's first American hydroelectric station, with just 25 kW of installed power produced by two small dynamos placed in a wooden shed, was energized by water rotating a small (107-cm diameter) wheel on the Fox River in Appleton, Wisconsin. The station was built for H. F. Rogers, a paper manufacturer, it powered 280 weak light bulbs, and it was in operation for seven years (Dyer & Martin, 1929). Godalming station, built by the Siemens brothers on the River Wey (in Surrey, south of Guildford), was also powered by a water wheel and its output was sufficient for just seven arc lights and 34 low-power incandescent bulbs (Electricity Council, 1973).

Those four pioneering projects—Holborn Viaduct, Pearl Street, Fox River, and Godalming—began two trends that, after continuing for more than

Figure 2.6 Dynamo room of Edison's first U.S. electricity-generating station in New York's Pearl Street. Reproduced from *Scientific American*, August 26, 1882.



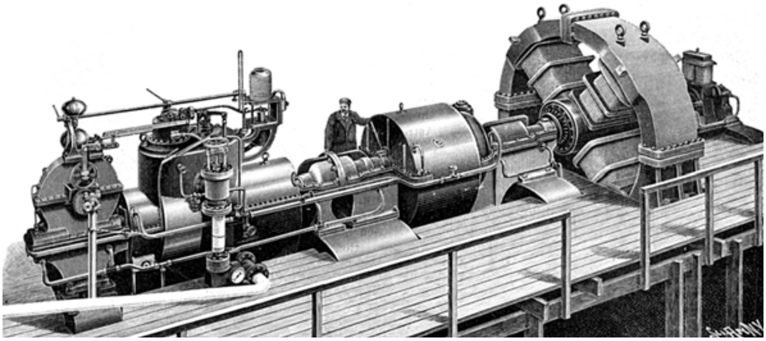
125 years, show no signs of weakening. The first transition has been, in many ways, perhaps the most consequential shift in the modern energy use as increasingly larger shares of fossil fuels are not used directly to provide heat and motion but to generate thermal electricity. The second transition has seen the primary electricity claiming a growing share of the total primary energy supply: Until the 1950s almost all of that generation was done by the kinetic energy of water (with a very minor contribution from geothermal flows), while since the 1950s primary electricity has originated from the combination of water and nuclear power joined (since the 1980s) by rising contributions from wind and most recently also by PV conversions. These different modes of electricity generation have had very different histories and they also face very different prospects.

There are at least four major reasons why thermal electricity generation took off so swiftly and has continued to expand so vigorously. The first one is an undoubtedly brilliant Edisonian design of an entirely new energy system for generating, transmitting, and converting electricity: Between 1880 and 1882 Edison obtained (in addition to nearly 90 patents for improved incandescent lights) 60 patents for electric dynamos and their regulation, 14 patents for electric lighting systems, 12 patents for electricity transmission, and 10 patents for electric meters and motors (TAEP, 2002). The second reason is that while more than 125 years after its invention Edison's grand concept of electricity system remains the foundation of the modern thermal electric industry, every one of its key components has been improved by a remarkable concatenation of technical advances that have made every aspect of the electric system more efficient, more reliable, and more durable.

Remarkable progress was achieved during the first 25 years following Edison's pioneering projects: Most notably, steam engines in power plants were displaced by steam turbines, direct current (DC) transmission gave way to alternating current (AC), and lights became much more efficient and longer-lasting. The steam engine, used by all U.S. electricity-generating plants during the 1880s, was an inferior energy converter when compared to the steam turbine that was patented by Charles A. Parsons in 1884 and that was rapidly scaled up to become the world's most powerful, and a very efficient, prime mover. Parsons's first 1884 machine was rated at just 7.5 kW, and at 1.6% its efficiency was inferior to Edison's Pearl Street station that converted less than 2.5% of chemical energy in coal to electric current sent to the financial district light (Parsons, 1936). By 1891 the largest steam turbine rated 100 kW, the first 1-MW unit was built in 1899 (Figure 2.7), and by 1907 Parsons put into operation a 5-MW turbine that converted coal to electricity with about 22% efficiency (Parsons, 1936).

Direct current, used by Edison to transmit electricity to his first customers, was replaced by AC transmission, a switch made possible by the introduction of efficient transformers; many inventors contributed to their perfection, but William Stanley introduced the prototype of modern current converters in 1885. AC was used already in some of the first small electric systems completed

Figure 2.7 The world's first 1-MW steam turbogenerator was installed in 1900 at Elberfeld plant in Germany. Reproduced from *Scientific American*, April 27, 1901.



during the late 1880s, but Edison had clung to his original DC choice for a while (not so much because of his famous stubbornness but because of his vested commercial concerns), but by 1890 the so-called "battle of systems" was over, with AC triumphant. And as far as the first widely used electricity converter was concerned, Edison's carbon-filament lights gave way to incandescent metallic filaments (osmium in 1898, tantalum in 1901 and, finally, tungsten in 1912).

Subsequent innovations have been neither continuous nor parallel. World War I, the worldwide economic depression of the 1930s, and World War II had an overwhelmingly negative effect on the growth of maximum capacities, efficiency improvements of steam turbines, and transmission networks. Stagnation of the 1930s was followed by higher war demand but most of it was met (given the urgency of the situation) by replicating the well-established designs rather than by introducing new techniques. As a result, the maximum capacity of U.S. steam turbines rose swiftly from 1 MW in 1900 to more than 200 MW by the early 1930s—but the latter size was not surpassed until the late 1950s. Exponential growth then pushed the maximum unit capacity to 1,000 MW (1 GW) by 1967 and at that time it was widely anticipated that turbogenerators of 2 GW and larger would be installed before 1980; but the largest units reached only about 1.5 GW and a reverse trend had actually led to smaller units in new thermal power plants, a trend that was greatly enhanced by a growing reliance on gas turbines used to produce electricity during peak demand periods.

Larger generating units using steam at higher temperature and higher pressure (the former rose from less than 200°C in the early twentieth-century plants to just over 600°C by 1960, while the latter rose from less than 1 MPa to more than 20 MPa during the same period) generated thermal electricity with much higher efficiency. Reliable U.S. statistics show average coal-to-electricity conversion efficiencies (with rates calculated using the output fed to a grid) rising from less than 4% in 1900 to nearly 14% in 1925, to 24% by 1950 (Schurr & Netschert, 1960) and to just over 30% by 1960, and by 1975 the performance of the best stations topped for the first time 40%. Subsequently the average heating rate stopped improving and it was still less than 34% in 2007 (EIA, 2009).

The third reason was the invention and rapid commercialization of a device that did not exist when Edison designed his first electricity-generating stations: In 1888 Nikola Tesla patented his electric induction motor, a device that made it possible to convert electricity into mechanical energy with high efficiency and with precise control. Within a few decades after their introduction electric motors became the dominant prime movers in all industries (more on this in the next section) and they had also revolutionized household work as they began to power washing machines (first on sale in the United States in 1907), vacuum cleaners (available since 1908), and household refrigerators (since 1912): Only in the United States had all of these machines diffused widely before World War II; in Europe and Japan their ownership became common only after 1945.

The fourth factor was the ability to harness the economies of scale by generating electricity in stations of increasingly greater capacity and by transmitting it by interconnected HV lines not only to serve entire territories of such large nations as Germany or France but to create important markets for international electricity trade, first in Europe and later also in North America. Larger stations were constructed by using multiple turbogenerators sharing large boilers. As a result, capacity of the largest U.S. thermal station rose from about 40 MW in 1900 to nearly 400 MW by the late 1930s and it surpassed 4 GW by the late 1970s, and the growth of average station capacities paralleled that rate by going from about 20 MW in 1930 to nearly 100 MW by 1960 and 400 MW by 1980 (Smil, 2003).

Because the HV transmission voltages are a direct function of overall capacities of thermal electricity-generating plants, they experienced a similar exponential growth, albeit interrupted by the Great Depression and World War II. American HV lines reached maxima of 110 kV just before 1910 and 230 kV by 1923 but (the single exception of the Hoover Dam–Los Angeles 287.5-kV line, completed in 1936, aside) their exponential rate of growth resumed only in 1954 with the introduction of 345-kV lines; 500-kV lines followed during the early 1960s and a new maximum was reached by 1965 when the first 1,100-km-long 765-kV line was installed by Hydro-Québec to transmit electricity from Churchill Falls in Labrador to Montréal.

International electricity trade began on a small scale between the two world wars and in Europe it progressed rapidly starting in the 1950s. Interconnections still limit the overall magnitude of the trade but since 2009 France, Belgium, the Netherlands, Luxembourg, and Germany have a fully integrated electricity market, with other EU partners expected to join soon. In North America the trade took off with the completion of HV direct current lines carrying Canadian hydroelectricity to U.S. markets. Because in 2005 the global electricity trade amounted to about 3.5% of all generation, there is a great potential for further growth in trade.

As thermal generation became the leading mode of electricity production, hydro generation retained its importance in all industrializing countries with suitable sites to develop. By the end of the nineteenth century increasingly higher concrete dams were built in the Alps, but the largest hydroelectric project was the Niagara Falls station completed in 1895 and enlarged in 1904 when its installed capacity of 78.2 MW (in 21 turbines of 3.7 MW) added up to 20% of the total U.S. generation (MacLaren, 1943). Another of its record-breaking aspects was the use of long-distance transmission of 5-kV and 25-Hz, three-phase, 11-kV current to Buffalo for municipal uses and for new large aluminum and carborundum plants attracted to the area by inexpensive electricity.

Hydro generation could expand thanks to two new turbine designs. The first successful water turbines predated the Edisonian electric system by decades: Benoît Fourneyron built his first reaction turbines during the late 1820s and the 1830s (Smith, 1980), and the machine that came to be known as the Francis turbine—although a product of many inventors, including Samuel B. Howd (1838 patent) and James B. Francis (improved design of 1848)—was commercialized by the 1860s (Hunter, 1979). An entirely new design suitable for high water heads, an impulse turbine driven by water jets discharged into peripheral buckets, was introduced during the 1880s by Lester Allen Pelton and in 1913 Viktor Kaplan patented his reaction turbine whose adjustable vertical-flow propellers have become a standard choice for low water heads.

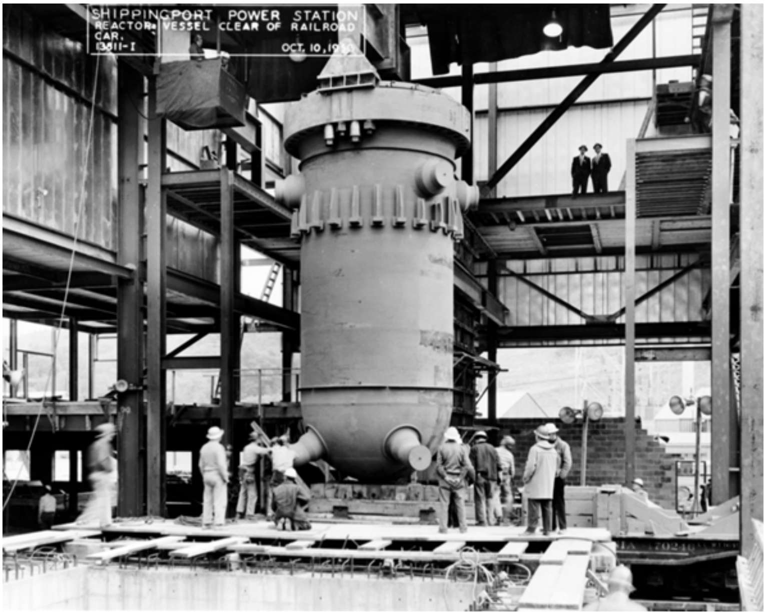
More than 500 hydro stations were completed before World War I, all but a few of them being low-capacity stations for local supply. The world's first giant hydro stations were built as a result of deliberate state support in the United States and in the USSR during the 1930s. The largest U.S. projects included a multi-station development directed by the Tennessee Valley Authority (a total of 29 dams) and the two dams of unprecedented size on the Colorado (Hoover Dam) and the Columbia (Grand Coulee). But the most intensive period of large-scale hydro construction came only after World War II: Between 1945 and 2000 more than 150 hydro stations with capacities greater than 1 GW were completed in more than 30 countries (ICOLD, 1998).

In contrast to gradual advances in hydro generation, nuclear electricity advanced from the basic scientific concept to the first commercial station in a remarkably short period of just 23 years. Milestones of this development have been described by its creators and by many historians of technical advances. Neutron's discovery in February 1932 (Chadwick, 1932) made it possible to think about the fissioning of suitable isotopes of the heaviest natural elements in order to release energy. Little more than half a year after Chadwick's announcement Leo Szilard formulated, and promptly patented, the basic idea of nuclear chain reaction. Fission's first experimental laboratory demonstration was made public in February 1939 (Meitner & Frisch, 1939) and Enrico Fermi directed the experiment that produced the first sustained chain reaction in a graphite reactor built under the bleachers of the University of Chicago stadium: It went critical on December 2, 1942 (Atkins, 2000).

The first demonstrations of nuclear power were the explosions of the two atomic bombs over Hiroshima and Nagasaki, and soon after the war's end Hyman Rickover began to develop nuclear reactor propulsion of submarines (Rockwell, 1992). *Nautilus*, the first nuclear-powered vessel, was launched in January 1955 and the same reactor design (General Electric's pressurized water reactor, PWR) was rapidly adopted under Rickover's direction for the first U.S. electricity-generating station completed in Shippingport, Pennsylvania, by December 1957 (Figure 2.8). But the first commercial nuclear electricity generation took place more than a year earlier, in October 1956, when the UK's Atomic Energy Agency commissioned Calder Hall station (4 × 23 MW, shut down in 2003, demolished in 2007).

This was followed by a decade of very slow progress and then by what remains the greatest wave of new nuclear power plant orders during the late 1960s and the early 1970s. This wave put the United States far ahead of other countries but its duration was brief: High oil prices brought by the OPEC-engineered energy crisis in 1973–1974 did not, as might have been expected, provide a greater stimulus for the development of new nuclear capacities; instead, the U.S. nuclear

Figure 2.8 Delivery of the reactor vessel for the Shippingport nuclear power station: The vessel's small size betrays the reactor's origin in submarine propulsion. Courtesy of the Library of Congress.



industry had to deal with constantly changing safety regulations, construction delays, and falling electricity demand. As a result, a typical U.S. nuclear plant was completed only after great delays and at a much higher cost than originally anticipated, and new orders began to decline. And although an accident at the Three Mile Island plant in Pennsylvania in March 1979 did not leak any radiation outside the containment structure, no new nuclear plants were ordered in the United States during the remainder of the twentieth century.

The United Kingdom continued with a scaled-down expansion, the USSR and Japan became other major builders, but France embarked on the boldest national nuclear program. Its core was a U.S. (Westinghouse pressurized water) reactor but its execution rested on building a large series of standardized plants (59, distributed around the country) and getting the benefits of cumulative experience and economies of scale. As a result, no other major economy was able to derive as much electricity from nuclear fission as France (recently about 78%). New capacities (almost solely in Asia) brought the total power installed in nearly 450 reactors to about 370 GWh in 2005 and increasing load factors (for the best stations more than 90%) raised the aggregate generation to just over 2.6 PWh. Besides France, the countries with the highest nuclear electricity share (setting aside Lithuania, which inherited a large Soviet nuclear plant at Ingalina that gave it a 70% nuclear share) are Belgium and the Slovak Republic (about 55%), Sweden (about 45%), and Switzerland (about 40%); Japan's share was 29%, the United States' 19%, Russia's 16%, India's 3%, and China's 2% (IAEA, 2009).

Before the recent rapid expansion of wind-generated electricity all other forms of primary electricity production were minor. The first geothermal developments date to the beginning of the twentieth century with Italy's Larderello plant in 1902. The first U.S. step toward commercializing geothermal generation was taken in 1960 with the Geysers plant north of San Francisco (now with rated capacity of 35 MW) while New Zealand's Wairakei came online in 1958 and Mexico's Cerro Prieto in 1970. All of these pioneering projects are based in high-temperature vapor fields. Subsequent developments have added stations of mostly small to medium size in the four countries as well as in the Philippines, Indonesia, and China.

France's La Rance (with 240 MW capacity, completed in 1966) remained the twentieth century's only small commercial tidal power plant, and designs for wave- and ocean current-driven plants did not progress beyond theoretical proposals and a few small, temporary demonstration devices. And before 2000 neither wind generation nor PV conversion made any global difference, and even in the nations that led their development their contribution remained well below 1% of the total electricity supply. Installed capacity of wind turbines reached 18 GW in 2000, no more than 2% of the global total, but given the low average load factor (on the order of 20–25%), wind-powered generation remained below 1% of the world total. And PV remained completely marginal, with peak capacity of just over 1 GW by 2000.

HISTORY OF PRIME MOVERS: FROM MUSCLES TO MACHINES

The history of prime movers mirrors the history of primary fuels in one important aspect: Human, and later also animal, muscles were the dominant prime movers during the entire human evolution until the early modern era, much as the biofuels had dominated the provision of energy needed for heat and light. But there was also an important difference, because in some societies the first inanimate prime movers (sails, water wheels, and windmills) eventually evolved to claim significant shares of power used in transport and production of goods long before a new wave of mechanical prime movers deriving their power from the combustion of fossil fuels made its appearance during the eighteenth and nineteenth centuries.

Human muscles were the sole prime mover during the hominin evolution as well as in all preagricultural societies organized to provide subsistence through foraging (gathering and hunting). Human exertions are limited by metabolic rates and by mechanical properties of human bodies, and before the domestication of draft animals the only way to enlarge their overall scope was to rely on combined action of people pushing or pulling heavy loads, sometimes with ingenious assistance by rolling logs or sleds (Smil, 1994). This is how Stonehenge, the great Egyptian pyramids, and the megalithic structures of Normandy, the Andean highlands, and Easter Island were built—but this multiplication of forces runs into obvious logistic constraints: The shape of a heavy object limits the number of people that can join to lift it, push it, or carry it, making those ancient construction feats even more remarkable.

Hand-made tools, ranging from simple wooden digging sticks to precisely finished stone arrowheads and bone needles, helped to improve the delivery of human power and mechanical devices—mostly variations of the three simplest designs (levers, inclined planes, and pulleys)—helped to expand its scope, but their sizes also had physical limits that were ultimately dictated by human metabolism and body structure. Basal metabolic rate (BMR) of all large mammals is a nonlinear function of their body mass M: When expressed in watts it equals $3.4M^{0.75}$ (Smil, 2008). This yields 70–90 W for most adult males and 55–75 W for females. Energy costs of physical exertion are expressed as multiples of the BMR: Light work requires up to 2.5 BMR, moderate tasks up to 5 BMR, and heavy exertions need as much as 7 BMR or in excess of 300 W for women and 500 W for men.

Healthy adults can work at those rates for hours, and given the typical efficiency of converting the chemical energy into the mechanical energy of muscles (15–20%) this implies at most between 60 W (for a 50-kg female) and about 100 W (for an 85-kg man) of useful work, and equivalents of five to seven steadily working adults performing as much useful labor as one draft ox and about six to eight men equaling the useful exertion of a good, well-harnessed horse. Of course, much higher rates, energized by anaerobic metabolism, can be sustained during brief spells. Humans were the most efficient prime movers when they walked inside large treadwheels where they deployed their largest back and leg muscles to generate rotary motion that was then used to lift heavy loads.

With the domestication of draft animals humans acquired more powerful prime movers, but because of the limits imposed by their body sizes and commonly inadequate feeding the working bovines, equids, and camelids were used to perform only mostly the most demanding tasks (plowing, harrowing, pulling heavy cart- or wagon-loads or pulling out stumps, lifting water from deep wells) and most of the labor in traditional societies still needed human exertion. Because draft animals have different weights (primary determinants of overall draft power), anatomies, metabolic efficiencies and endurances, and because their potential power can be used to the best possible effect only with proper harnessing and well-designed tools, it is impossible to offer any simple conclusions regarding the substitution of human labor by animal work.

Working bovines (many cattle breeds and water buffaloes) weigh from just 250 kg to more than 500 kg. With the exception of donkeys and ponies, working equines are more powerful: Larger mules and horses can deliver 500–800 W compared to 250–500 W for oxen. Some desert societies also used draft camels, elephants performed hard forest work in the tropics, and yaks, reindeer, and llamas were important pack animals. At the bottom of the scale were harnessed dogs and goats. Comparison of plowing productivities conveys the relative power of animate prime movers. Even in the light soil it would take a steadily working peasant about 100 hours of hoeing to prepare a hectare of land for planting; in heavier soils it could be easily 150 hours. In contrast, a plowman guiding a medium-sized ox harnessed inefficiently by a simple wooden yoke and pulling a primitive wooden plow would do that work in less than 40 hours; a pair of good horses with collar harness and a steel plough would manage in just three hours.

Arable farming relying solely on human labor was thus suited only for garden-sized or small-field cultivation and only the use of draft animals made it possible to cultivate larger fields. But their effective use required adequate feeding and efficient harnessing, and their satisfactory combination became widespread only during the early modern era. The ability of bovines to survive solely on cellulosic feed (grasses or crop residues they can digest thanks to their microbial symbionts) made them the least demanding and the least expensive draft animals—but commonly inadequate nutrition and hence low body weight, limited endurance, slow pace of work, and ineffective harnessing (by a variety of head and neck yokes) restricted their draft power to mostly less than 400–500 W per animal. During the nineteenth century the European farmers could do 25–30% more work in a day with a pair of horses than with a team of four oxen—and horses could work for up to 20 years, while oxen lasted normally for less than 10.

But efficient use of horses requires expensive harnessing: ancient throat-and-girth and breastband harnesses (pictured on Egyptian monuments or in early Chinese frescoes) could not be used for heavy field work or for pulling loaded wagons and only the invention of collar harness in the Han dynasty China and its gradual westward diffusion opened the way for efficient use of horse power. But even after horse collars (fitted to animal's shoulders) became the norm in Europe (before 1200) their cost, as well as small sizes of medieval horses and shortages of grain feed, meant that most of the heavy field and transport work continued to be done by oxen harnessed by neck or head yokes.

Comparing the performance of wheeled transport is obviously heavily influenced by the quality of roads and the design of wheels and wagons: No draft animal could make good progress on soft muddy or sandy roads, even less so when pulling heavy carts with massive wooden (initially full disk; spokes came around 2000 BCE in Egypt) wheels. When expressed in terms of daily mass-distance (t-km), a man pushing a wheelbarrow rated just around 0.5 t-km (less than 50-kg load transported 10–15 km), a pair of small oxen could reach 4–5 t-km (10 times the load at a similarly slow speed), and a pair of well-fed and well-harnessed nineteenth-century horses on a hard-top road could surpass 25 t-km.

All animate prime movers have very limited unit capacities, very high mass/power ratios, and specific demands to support their best performance. Humans can sustain hours of useful work at 50–100 W, lighter and poorly harnessed draft animals can deliver 200–500 W, and even the most powerful horses can work steadily at no more than about 800–900 W. Higher output requires combining forces, a precept that all preindustrial cultures followed during the construction of their massive stone monuments. Domenico Fontana's erection of an Egyptian obelisk (originally brought to Rome during Caligula's reign) in St. Peter's Square in 1586 is an outstanding illustration: 140 horses and 900 men were needed for the job (Fontana, 1590). And before the introduction of internal combustion engines the world's first combines in California and Washington were pulled by more than 30 horses.

Mass/power ratio is a critical characteristic of prime movers because it allows for universal comparisons across the entire evolutionary span; obviously, the lower the ratio the more powerful the prime mover. Commonalities of mammalian metabolism make the mass/power ratio for working humans and animals very similar, at nearly 1,000 g/W. An 80-kg man (BMR of 90 W) engaged in moderately heavy work (up to 5 times BMR, or 450 W) with typical chemical/mechanical efficiency of 0.2 will produce 90 W and require nearly 900 g/W; a large horse (750 kg) working exactly at the rate of one horsepower (745.7 W) will have mass/power ratio of just over 1,000 W/g.

The first commonly used inanimate prime movers were sails on river-borne vessels and in coastal shipping and later deployed for voyage on the open ocean. Sails are simple fabric airfoils used to convert wind's kinetic energy by generating lift (and drag) and, regardless of their specific design and efficiency, they can deliver optimal performance only when propelling ships whose drag is minimized by appropriate (stable and hydrodynamic) hull design and whose steering is optimized by a rudder (Marchaj, 2000; Block, 2003). All ancient vessels had square sails, and triangular sails made their appearance only in the early medieval era. During the late Middle Ages the combination of larger and better adjustable square and triangular sails made it possible to sail closer to the wind. Such ships, when equipped with magnetic compass, made the great journeys of European world discovery between the late fifteenth and the early nineteenth centuries.

The first stationary inanimate prime movers came into use long after the first use of sails—but we cannot conclusively date the origins of the first such device, a simple horizontal water wheel rotating around a sturdy wooden vertical shaft and directly driving an attached millstone. Lewis (1997) put its invention as early as the third century BCE (perhaps in Alexandria) but its first surviving description comes from the first century BCE (Antipater of Thessalonica), and by 27 BCE Vitruvius was describing more efficient vertical wheels (rotating around a horizontal shaft), turning the millstones by right-angle gears and powered by water impacting at their bottom (undershots), just above their midline (breastwheels), or falling from above in the most efficient overshots. These wheels became relatively common in some parts of the Roman world already by the second century CE (Wikander, 1983), their numbers kept increasing during the subsequent centuries, and the Domesday book (a remarkable inventory of England's economic capacities in 1086) listed about 6,500 of these machines used to do many other tasks besides milling grain (Holt, 1988).

While in many parts of Europe the Middle Ages saw an increasing number of watermills and a greater variety of their uses (with more machines built as more efficient vertical wheels with water supply either overhead or at wheel's breast level), typical capacities remained low. As a result, even during the early eighteenth century a typical European mill would rate only a few kW. The most notable exception, an assembly of 14 massive (12-m diameter) wheels completed by 1685 at Marly to power the pumps delivering the Seine water to Louis XIV's Versailles fountains, never worked at its full capacity and it delivered just over 4 kW (Klemm, 1964).

The origin of windmills, the second most important preindustrial mechanical prime movers, is even more obscure than is the emergence of water wheels (Lewis, 1993). What we know with certainty is that the first devices—crudely made, very inefficient, with cloth sails mounted on vertical wooden axes turning millstones without any gearing—were used in Sistān (in today's eastern Iran) and that their subsequent westward diffusion, beginning during the eleventh century, brought them to Byzantine lands and from there the Crusaders introduced them to Atlantic Europe. During the Middle Ages Europe's lands bordering the Atlantic acquired the world's largest concentration of windmills and retained this primacy until the advent of the nineteenth-century industrialization.

All of the early Atlantic machines pivoted on a massive wooden central post that was kept perpendicular by sturdy diagonal quarter bars; their sails had to be turned into wind manually, they were rather unstable and inefficient, and their low height limited their power (which is proportional to the cube of wind speed). During the early modern era they were gradually replaced by tower (cap) mills: only their cap, mounted on a fixed tower, would be turned into the wind, at first manually from a gallery, since the mid-eighteenth century automatically by using a fantail. The largest deployment of tower mills took place in the Netherlands for the drainage of large polders and creation of new land for fields and settlements (Husslage, 1965; Hill, 1984). By the nineteenth century windmills were leading sources of mechanical power also in the southern part of England, in Picardy, Belgium, coastal Germany, Denmark, and southern Sweden. Massive diffusion of American windmills was due to the westward expansion across the Great Plains, where tower mills (with narrow blades or slats mounted on solid or sectional wheels and equipped with governors and rudders) became indispensable for pumping water for households, cattle, and steam locomotives (Wilson, 1999; Figure 2.9).

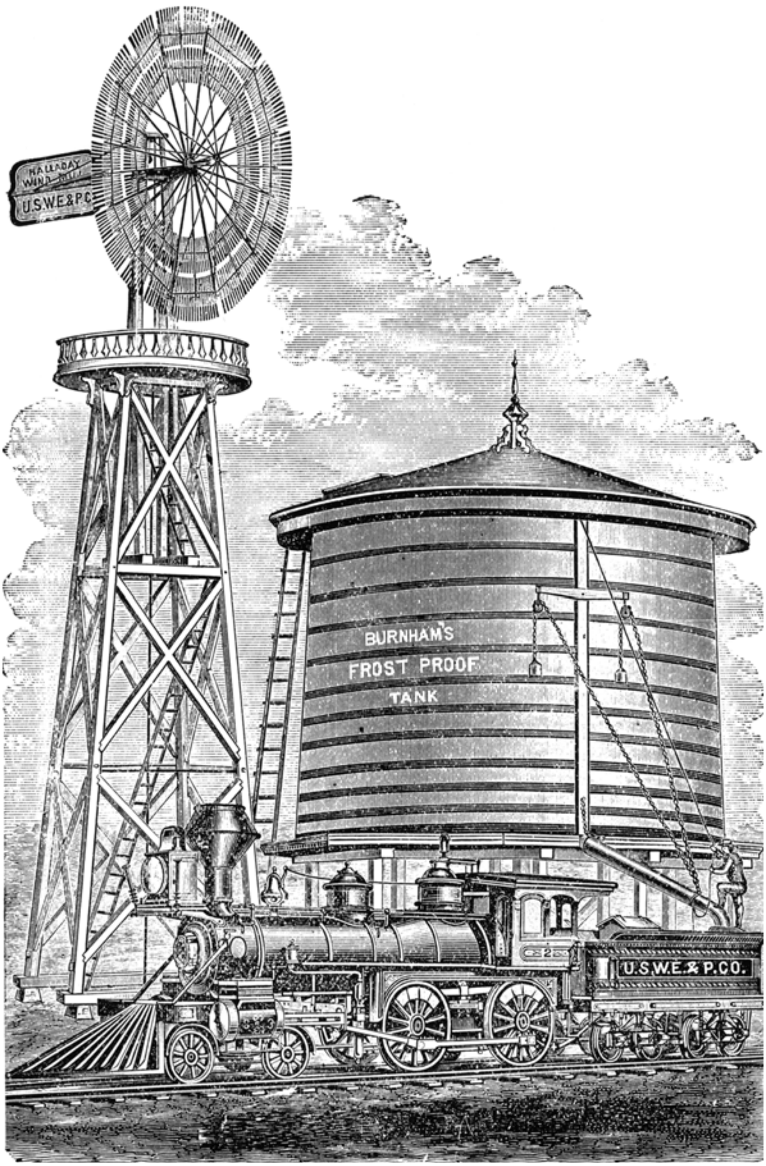
Useful power of common medieval windmills was certainly lower than the power of typical contemporary water wheels, but the first reliable measurements of windmill performance were done only during the 1750s. At that time John Smeaton found a common Dutch mill (with 9-m sails) as powerful as 10 men or 2 horses, that is, conservatively converted, with capacity of about 1 kW (Smeaton, 1796). Larger mills could have wind-shaft power well in excess of 10 kW (a preserved 1648 marsh mill was appraised at about 30 kW) but large gearing losses (on the order of 50–60%) reduced the useful power considerably.

Typical useful power ratings were less than 1 kW for the American Great Plains wheels, 1–2 kW for small and 2–5 kW for large medieval European post mills, 4–8 kW for widely used early modern European tower mills, and 8–12 kW for the largest nineteenth-century devices in countries around the North Sea. By 1900 the total number of windmills in that region was in the tens of thousands and de Zeeuw (1978) estimated their aggregate power at no less than 100 MW. For comparison, during the second half of the nineteenth century sales of smaller American windmills reached several million units and their aggregate capacity in 1900 was estimated at about 90 MW by the U.S. Bureau of Census (1975)—but it was put at nearly 500 MW by Daugherty (1927).

The first commercial steam engines fueled by coal and designed by Thomas Newcomen (1663–1729) during the first decade of the eighteenth century were so inefficient that they could operate profitably only in coal mines, mostly for pumping water from pits (Rolt & Allen, 1977). Because the engine's piston was cooled with every stroke (condensation of steam took place on its underside), Newcomen's machine converted no more than 0.5% of coal's chemical energy into slow reciprocating motion. James Watt's (1736–1819) famous improvements, patented in 1769, included a separate steam condenser, an insulated steam jacket around the cylinder, and an air pump to maintain vacuum (Robinson & Musson, 1969). Watt also designed a double-acting engine (with piston driving also on the down stroke) and a centrifugal governor to maintain constant speed with varying loads.

By 1780 Watt's engines had efficiencies in excess of 2% and they began to be installed by a variety of industrial enterprises: Nearly 500 of them were

Figure 2.9 A late nineteenth-century U.S. Halladay windmill. Reproduced from Wolff (1900).



built by 1800. Because Watt refused to work with high pressures any developments of pressurized engines had to wait for the expiry of his patent. Once that took place (in 1800) the progress of mobile steam engines both on water and on land was fairly rapid. River steamboats began regular commercial service before 1810, the English Channel was crossed for the first time in 1815 and the 1830s saw the first trans-Atlantic crossings fully powered by steam, and the first scheduled railway service was offered by 1825 (Smil, 1994).

Steam engines remained the dominant mechanical prime mover during the entire nineteenth century and by 1900 their record ratings were unit power of 3 MW (compared to 100 kW in 1800), pressure of 1.4 MPa (100-fold increase above the 1800 level), and efficiency of just above 20%, an order of magnitude better than at the beginning of the nineteenth century. But the machines had their inherent disadvantages, above all the enormous size and mass of all high-capacity units due to high mass/power ratios and relatively poor conversion efficiency. The first drawback made them unsuitable for road transport, eliminated them from any serious consideration in powered flight, and also made it impractical to build larger units (in excess of 5 MW) required for the increasing capacities of thermal electricity generation.

And the just cited maximum of more than 20% applied only to massive stationary triple- and quadruple-expansion engines; smaller shipborne engines were about 10% and locomotive engines only 6–8% efficient. Not surprisingly, once a better alternative became available steam engines retreated fairly rapidly: Already by 1900 it was clear that they were an inferior choice as the prime movers for thermal electricity generation when compared to steam turbines; a few years later mass production of reliable gasoline engines ended a brief era of steam-powered automobiles (Ford's famous Model T was introduced in 1908); and before the beginning of World War I it was clear that it was only a matter of time before diesel engines would displace steam engines in shipping and on railroads.

The steam turbine had a particularly steep improvement curve. The first small prototype built by Charles Parsons in 1885 had power of only 7.5 kW and efficiency of less than 2% (Parsons, 1936). By 1890 a Newcastle station was installing units of 75 kW working with efficiency of just over 5%, the first 1-MW unit began to generate electricity at a German plant in 1899 (see Figure 2.7), and the largest units installed before the beginning of World War I rated 20–25 MW and had efficiencies around 25% (Parsons, 1936). This means that the machine that is still the world's most powerful continuously working prime mover moved from a prototype to a multi-MW commercial choice in less than two decades. As with so many other innovations, the rate of advances slowed down between the two world wars but steep gains began again during the late 1940s and continued until the 1970s: Since that time there have been no fundamental design and performance gains.

Superiority of steam turbines is perhaps best illustrated by contrasting their current top ratings with those of the most advanced steam engines at the beginning of the twentieth century (Smil, 1994, 2003). Their rotation speeds differ by an order of magnitude (typically less than 100 rpm vs. as much as 3,600 rpm) as do their working pressures (typically less than 2 MPa vs. as much as 34 MPa), their maximum capacities differ by two orders of magnitude (less than 5 MW vs. about

1.5 GW), and at just 1–3 g/W mass/power ratios of steam turbines are less than 1% those of steam engines (250–500 g/W). As a result, steam turbine-driven electricity generation needs only a fraction of the materials to build the machines and it avoids construction of the enormous buildings that would be needed to house gargantuan steam engines.

This is an apposite place to describe in some detail the key benefits of electric motors, whose rapid diffusion was made possible by solving the key challenges of large-scale electricity generation and transmission during the last two decades of the nineteenth century. Long before these converters revolutionized household work they brought an even more fundamental change to industrial production in general and to labor-intensive manufacturing in particular. The steam engine, the first widely used coal-powered prime mover, did not change the way mechanical energy was distributed in factories that used to rely on power produced by water wheels: ceilings in textile or machining plants remained full of long line shafts whose rotations were transmitted (usually by belts) to machines on the factory floor. This was expensive, awkward, dangerous, and inconvenient, as accidental damage to any part of the system forced its complete closure while even a partial production capacity required the entire system to operate.

Electric motors eliminated the need for converting reciprocating power delivered by steam engines into rotary motion by using line shafts and long ceiling-to-floor belts. No less importantly, they allowed precise, on-demand, convenient power supply to individual machines on the factory floor while freeing the ceilings for allowing adequate natural or electric lighting (Schurr, 1984). They also eliminated another disadvantage shared by steam and internal combustion engines, constant vibration. Electrification of industrial manufacturing was completed first in the United States (during the 1930s), then in Europe (by the 1950s), and many low-income countries went straight from the ancient use of animate prime movers to reliance on electric motors: Irrigation powered by an electric pump as opposed to by animals lifting water from a well is just one of many examples of this transition.

Electric motors have powered yet another important energy transition, from steam to electricity on railroads. In freight transport steam was displaced primarily by heavy diesel engines (this transition was complete in North America and most of Europe by the late 1950s), but all of the world's fast trains are now powered by electricity. This trend began in 1964 with Japan's *Tōkaidō shinkansen* and in 1981 France was the first European country to introduce comparably fast (and eventually even faster) service with its TGV (*Train à Grande Vitesse*) trains, whose variants now operate also across the Channel and in the United Kingdom (*Eurostar*), in Belgium (*Thalys*), Spain (*AVE*), and in Germany (*InterCity*).

That remarkable innovative decade of the 1880s saw not only the introduction of the steam turbine, the world's most powerful continuously working prime mover, but also the first successes of the gasoline-fueled internal combustion engine, the machine whose aggregate production has since far surpassed the totals for any other mechanical prime mover (leaving the electric motors aside). The steam engine is an external combustion machine, with water heated in a boiler and steam led into the piston chamber. In contrast, in internal combustion devices the working medium (hot gas) is produced by combustion of fuel inside the engine (intermittently in piston engines, continuously in gas turbines).

Such devices had a conceptual history predating 1800 with many failed designs and prototypes introduced during the first half of the nineteenth century. The decisive breakthrough came only in 1860 with a non-compressing (and hence low-efficiency) machine built by Jean Joseph Étienne Lenoir. Theoretical design of a four-stroke internal combustion engine was done first by Alphonse Eugène Beau (later known as Beau de Rochas) in 1862, but the first practical design of a four-stroke compression engine, by Nicolaus August Otto, followed only in 1876 (Sittauer, 1972; Payen, 1993). Otto's first engine, introduced in 1866, was a two-stroke non-compression engine fueled by coal gas; in 1874 its improved version was still very heavy (mass/power ratio of about 900 g/W) but more than twice as efficient (about 10%).

The first four-stroke compression engine had efficiency of about 17% and mass/power ratio of just 250 g/W, much lower than that of any similarly sized contemporary steam engine. Otto's company eventually produced nearly 50,000 of these gas-fueled machines with the most common ratings between 5 and 10 kW and with aggregate capacity of about 150 MW. The next advance was to design a four-stroke compression engine running on gasoline, a fuel whose energy density is roughly 1,600 times that of the coal gas used in Otto engines and whose low flashpoint makes engine starting easy.

This machine was first designed and built independently by three German engineers: by a duo of inventors in Stuttgart and by an experienced mechanic in Mannheim (Walz & Niemann, 1997). Gottlieb Daimler and Wilhelm Maybach had a prototype ready in 1883, the first motorcycle engine in 1885, and the first car engine (just 820 W) a year later. Karl Friedrich Benz completed his first two-stroke gasoline-fueled machine also in 1883 and used his first four-stroke 500-W machine to propel a three-wheeled carriage in 1886 (Figure 2.10). Rapid advances followed during the last 15 years of the nineteenth century. By 1895 Daimler and Maybach were selling a 4.5-kW engine with mass/power ratio of less than 30 g/W, and in 1900 came a 26-kW four-cylinder engine with mass/power ratio of less than 9 g/W that was used to power Mercedes 35, a high-performance vehicle that came to be seen as the first modern automobile.

Otto cycle four-stroke gasoline-fueled internal combustion engine thus became a mature machine in just a single generation after its invention and while the technical advances of the twentieth century improved its performance (thanks above all to higher compression ratios made possible by the addition of anti-knocking compounds to gasoline) and increased its reliability (electronic controls of ignition) there were no fundamental changes of the basic design. Today's automotive engines have power ranging from only about 50 kW for urban mini cars to about

Figure 2.10 Gasoline-powered three-wheeler by Benz & Cie., as shown at Munich machinery exhibition in 1888. Reproduced from *Scientific American*, January 5, 1889.

375 kW for the Hummer, their compression ratios are typically between 9:1 and 12:1 and their mass/power ratios are mostly between 0.8 and 1.2 g/W. But even the most powerful gasoline-fueled engines (in excess of 500 kW) are too small to propel massive ocean-going vessels or to be used by the largest road trucks and off-road vehicles or as electricity generators in emergencies or in isolated locations.

Those duties are filled by another internal combustion engine, one that initiates combustion through high compression and hence is inherently more efficient. Rudolf Diesel laid the conceptual foundation of this engine during the early 1890s and then, with support and cooperation of Heinrich von Buz, general director of the *Maschinenfabrik Augsburg*, he developed the first practical engine by 1897. Its official testing showed power of 13.5 kW and a high mass/power ratio of 333 g/W—but with thermal efficiency of nearly 35% and mechanical efficiency of about 75% its net efficiency was just over 26%, a performance superior to any contemporary converter of fuel to mechanical energy (Diesel, 1913).

Even so, that heavy machine had to undergo a period of improvements before it was ready to conquer first the shipping market and then railroad and heavy road transport. First diesel engines in marine vessels were installed in submarines already a decade before World War I and by the beginning of World War II about a third of all ocean-going vessels were powered by diesels. The transition from steam engines to diesels was completed quite rapidly after World War II as the decades of vigorous economic growth led to a steady expansion of intercontinental trade and construction of increasingly powerful vessels. As a result, power of the largest two-stroke, low-rpm marine diesels rose from less than 5 MW during the early 1930s to just over 10 MW by the late 1950s and by 2008 it has surpassed 85 MW in order to propel the largest, and fastest (more than 45 km/h), container ships carrying more than 10,000 steel boxes.

The first automotive diesel engines came in 1924 for trucks and in 1936 Mercedes-Benz 260D (a heavy, 33.5-kW, four-cylinder, six-seat saloon car) became the first diesel-powered passenger car (Williams, 1982). But the real transition to diesel-powered road vehicles got fully underway only after World War II. By the 1960s virtually all heavy trucking was converted to diesels, and diesels also propelled all heavy agricultural machines and various off-road vehicles used in construction and mining. Introduction of low-sulfur diesel fuel (<50 ppm S) and, most recently, of ultra-low-sulfur diesel (<10 ppm S) has made diesel-powered passenger cars more acceptable: They claim a tiny share of the North American market, but in Europe diesel car sales topped those of gasoline-fueled cars in 2006.

The only new prime mover introduced during the twentieth century was the gas turbine, a machine whose concept goes back to the last decade of the eighteenth century but whose first successful prototypes were built during the late 1930s. World War II accelerated the development of jet engines and the British industries tried to capitalize on Frank Whittle's (and Frank Halford's) pioneering designs by launching the first programs to develop jet-powered passenger planes. Geoffrey de Havilland began to develop Comet, the first commercial jetliner powered by de Havilland's Ghost turbojet, for the British Overseas Airways Corporation (BOAC) in 1946. The plane entered service on May 2, 1952 but the entire Comet fleet was grounded in 1954 after several fatal accidents caused by catastrophic decompression of the plane's fuselage.

As a result Boeing's 707, with four Pratt & Whitney's 84-kN JT3D engines, became the most successful pioneering jetliner design in 1958, and the company strengthened its primacy with the introduction of the first wide-body plane, Boeing 747, with four Pratt & Whitney's 210-kN JTD engines, in 1969. Eventually only two companies, America's Boeing and the European Airbus, survived the competition to produce all of the world's large commercial jetliners, and all of their planes are powered by gas turbines made by one of the three remaining makers of jet engines, America's GE and Pratt & Whitney and British Rolls-Royce, or their consortia. Advances in the performance of jet engines are best illustrated by contrasting the performance of the first commercial designs (turbojets) with the latest turbines (all turbofans).

Comet's de Havilland turbojet Ghost engine had thrust of 22.25 kN while today's most powerful turbofan, GE 90-115B, rates 512 kN (a 23-fold increase); the latest engines have thrust/weight ratio in excess of 6 compared to just 0.17 for the Ghost. And the first turbofans, introduced during the late 1950s, had bypass ratio less than 0.5 (i.e., only half of the air entering the engine was compressed by a frontal fan and then led around the engine's core) while the latest turbofan models have bypass ratios as high as 11:1 (i.e., only 9% of all air entering the engine passes through its core where it oxidizes kerosene, and 91% of the thrust comes from the cool air bypassing the core). As for the conversion efficiency, specific fuel consumption of the latest turbofans is only about half that of the earliest commercial turbojets of the 1950s (Ballal & Zelina, 2004).

Development of larger stationary gas turbines—used primarily for electricity generation during peak demand hours as well as to power industrial compressors—had proceeded in parallel with the introduction of more powerful jet engines. The largest gas turbines used to generate electricity reached the capacity of 100 MW in 1976 (with about 32% efficiency) and by 2008 the most powerful unit was a Siemens turbine rated at 340 MW (Siemens, 2009). Such turbines do not work alone: Their waste heat is used by attached steam turbines and the resulting combined-cycle arrangements have net efficiencies as high as 60%. In addition to these large machines, smaller aeroderivative turbines (essentially grounded jets) have become increasingly popular since the 1980s thanks to their flexibility and rapid installation.

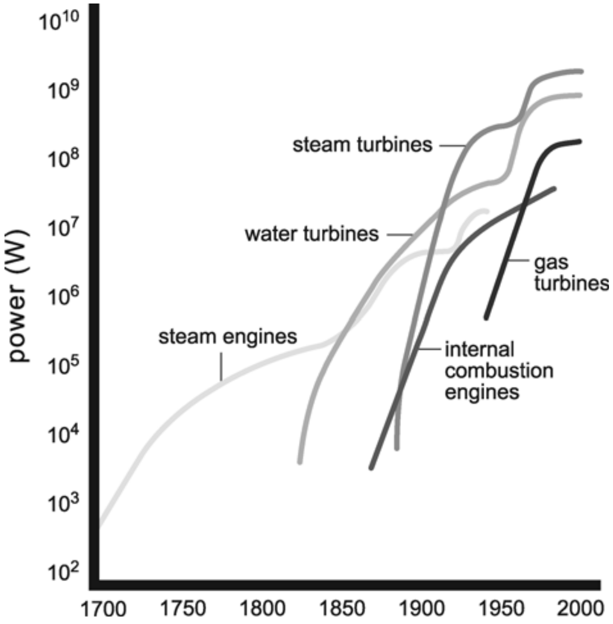
As with so many other technical advances, long-term comparisons of prime movers show some astounding gains since the invention and perfection of fossil-fueled prime movers. Until about 10,000 years ago the peak performances were limited by the power of human muscles, affording short-term maxima of 100–200 W of useful work, and sustained exertion at 50–100 W. Domestication of draft animals increased sustained work rates to mostly 300–500 W in antiquity (limits imposed by the animal size, feeding, and harness) and to 400–800 W after 1800, when the brief exertions of heavy draft horses could deliver more than 2 kW/animal. Maximum sustained performance of the most powerful animate prime movers thus rose by an order of magnitude, from about 60–80 W for women and men to 600–800 W (average for good horses).

Power of water wheels, the first inanimate prime movers, rose slowly from small machines of the late antiquity capable of just 10^2 W to larger wheels with power of a few kW (10^3 W) after 1700 and to as much as a few hundred kW (10^5 W) by 1850; windmills, whose adoption came more than a millennium after the first conversions of flowing water, also had a slow capacity growth culminating in machines of no more than 10^4 W by the late nineteenth century. Capacities of water wheels, the largest preindustrial inanimate prime movers, thus rose by three orders of magnitude (thousand-fold), but it took them about two millennia to do so. In contrast, capacities of steam engines, the first postindustrial inanimate prime movers, grew exponentially: They surpassed those of the largest water wheels in less than half a century after their commercial introduction in the early eighteenth century; by 1850 the unit maxima were above 10^5 W and by 1900 they exceeded 1 MW (10^6 W).

By that time the most powerful prime movers were water turbines whose steep-capacity ascent began during the 1830s and whose brief primacy was surpassed by steam turbines introduced during the late 1880s. A century later these machines remain the world's most powerful continuously working prime movers (maxima up to 1.2–1.5 GW, with common sizes of 200–800 MW), but water turbines commonly used in large hydro stations are not far behind with capacities of 100–600 MW. Capacities of the largest stationary fossil-fueled prime movers thus increased from 10^3 W (less than 3 kW for Newcomen's steam engines of the early eighteenth century) to 10^9 W (largest steam turbogenerators), or six orders of magnitude (a million-fold jump) in three centuries—but 99.9% of that rise took place during the twentieth century as the maximum rating of steam turbogenerators rose from 10^6 to 10^9 W (Figure 2.11).

Finally, I must stress the continuity of prime movers and hence the indispensable roles played by their dominant forms in the development of their eventual substitutes. All early coal-mining was powered entirely by animate energies: men working at coal faces, women and children (and later also ponies) moving the cut fuel to loading points, and, again, women ascending ladders with back loads, or horses on the surface walking in circles and turning the whims lifting coal from deeper shafts. The steam era was thus made possible only by muscular work whose brutality and dangers is perhaps best conveyed by Émile Zola's descriptions in *Germinal*, a shockingly faithful portrayal of conditions in coal mines of northern France of the late 1860s. In turn, steam engines powered the late nineteenth-century manufacturing that produced the devices and

Figure 2.11 Maximum capacities of inanimate prime movers, 1700–2000. Based on Smil (1994).



infrastructures of electric industry, and steam engine-powered tankers continued to transport crude oil, whose refining produces gasoline and diesel fuel for internal combustion engines, until after World War II.

Naturally, this continuity applies also to the now unfolding transition from fossil fuel to the conversion of renewable energies. Perhaps most notably, wind turbines are now seen as great harbingers of renewability, about to sever our dependence on fossil fuels. But their steel towers are made from the metal smelted with coal-derived coke or from recycled steel made in arc furnaces, and both processes are energized by electricity generated largely by turbogenerators powered by coal and natural gas combustion. And their giant blades are made from plastics synthesized from hydrocarbon feedstocks that are derived from crude oil whose extraction remains unthinkable without powerful diesel, or diesel-electric, engines.

QUANTIFYING THE TRANSITIONS: UNCERTAINTIES AND TRENDS

Quantifying the global preindustrial consumption of biofuels can be done with confidence only as far as the absolute magnitude is concerned. At the beginning of the nineteenth century the total was at least 20 EJ (in terms of air-dry biomass containing 10–15% moisture) and it is unlikely that by the year 2000 it rose above 50 EJ/year. But because most of the fuelwood used in low-income countries is never traded but collected by women and children for their family use, and because the share of crop residues used for fuel is even more difficult to quantify, we cannot be certain if, as FAO (1999) estimated for the late 1990s, 63% of all harvested wood was burned as fuel or if the share amounted to just 55% or 70%, or if the burning of crop residues in the field, their recycling, and feeding to animals left just 20% or as much as 30% of their total mass for fuel. The difference between the lower and upper estimates adds up to about 10 EJ for the year 2000 (20% of the likely maximum), and the relative uncertainties are even greater for earlier periods.

Only a few countries have some fragmentary data that make it possible to reconstruct their wood combustion in some of their regions during parts of the eighteenth and nineteenth centuries, but it is unclear how applicable such figures are even for other regions within the same country. For most of the world's regions there are simply no representative aggregate or per capita rates and it is highly questionable to extrapolate any available local (and invariably time-limited) examples to larger territories and longer time spans. As it is impossible to reconstruct any national (or global) totals of wood consumption during the preindustrial era, we can only quote some revealing approximate averages.

My reasoned estimate of typical Roman fuel needs (during the early imperial era) was at least 10 GJ/capita (Smil, 2010a). Galloway, Keene, and Murphy (1996) found that in 1300 the average demand in London (including all household and manufactures) topped 1.5 t of air-dry wood per capita, or roughly 25 GJ/capita. In parts of forest-rich Germany annual use was on the order of

50–60 GJ/capita by the eighteenth century (Sieferle, 2001) and fairly reliable U.S. data indicate that by 1850 the country consumed annually as much as 97 GJ/capita for all uses. Surveys of traditional rural energy use done in China of the late 1970s found that in a family of four to five people 12–15 GJ/capita were needed for cooking and water heating and that at least 3.3 MJ/m^2 were needed daily for minimum heating during four to five winter months in North China, an equivalent of 4–5 GJ/capita (Smil, 1993). Consequently, minimum annual wood and crop residues use in Chinese villages added up to 16–20 GJ/capita.

The simplest estimates of the past biomass energy use thus multiply the best available approximations of population totals by the most plausible annual per capita consumption rates. I have used continental disaggregations for both the population totals and time-differentiated (1800, 1850, and 1900) per capita consumption means (ranging from the lows of 10 GJ in Africa for all periods to the high of 90 GJ in North America in 1850 and 30 GJ/capita in 1900) to estimate the global biomass energy use during the nineteenth century. These calculations produce approximate totals of 20 EJ of biomass energy in 1800, about 25 EJ in 1850, and 22 EJ in 1900. My most likely range for the year 2000 is 40–45 EJ, the higher total corresponding to the mean (45 ± 10 EJ) offered by Turkenburg et al. (2000). These totals imply a doubling of biofuel harvests during the twentieth century, and this absolute growth has been accompanied by declining per capita uses everywhere except in the sub-Saharan Africa.

In contrast to scarce information regarding the use of biofuels, we have numerous figures for the British coal extraction going back to the late sixteenth century as well as data for other early (eighteenth century) European coal producers and American statistics going back to the beginning of the nineteenth century. Given the relatively recent beginnings of oil and gas production (dating to the 1860s) we have even better information regarding the cumulative output of those hydrocarbons, whose output can be also converted to common energy equivalents with a high degree of accuracy. Energy densities of those fuels span only narrow ranges (41–42 MJ/kg for crude oils and 35–40 MJ/m^3 for natural gases) while for bituminous coals the difference between the best and the poorest varieties is at least 7 MJ/kg (20–27 MJ/kg); the best lignites contain as much as 18 MJ/kg the poorest ones have less than 10 MJ/kg. Moreover, all of these rates change in time as coal extraction proceeds to tap seams of lower quality. These differences are a major source of inevitable errors in expressing coal production in common energy equivalents.

Finally, fuel output must be adjusted for pre-consumption losses and for non-energy uses. Losses during coal sorting, cleaning, transportation, and storage are considerably smaller than the inherent uncertainty of converting bituminous coal and lignite extraction to energy equivalents and I have used 1% reduction throughout; transportation oil spills and losses of liquids and gases during refining have been also reduced to a similarly marginal level, while natural gas leakage from pipelines amounts to between 1% and 2% of the transported fuel. Non-fuel uses of coal (mainly as a feedstock for chemical syntheses) are negligible on the global scale but crude oil refining yields many products that are used as feedstocks, lubricants, and paving materials, and natural gas is the principal feedstock for the production of ammonia, methanol, and ethylene, the precursors of an enormous variety of synthetics.

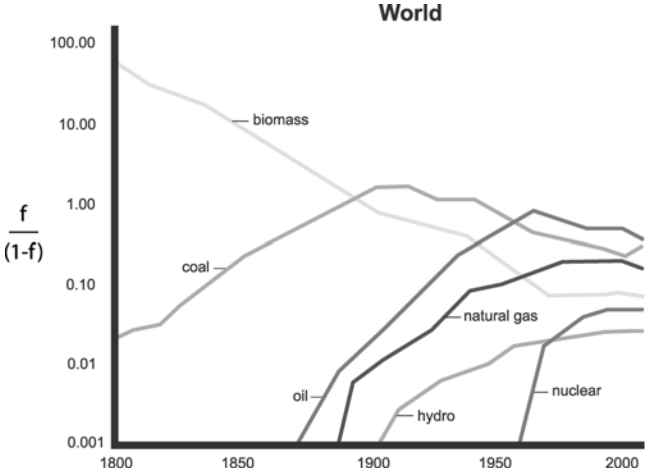
In order to account for the losses and non-energy uses of hydrocarbons I have subtracted 15% from the recent production of crude oil and 6% from the recent extraction of natural gas. Detailed information on specific losses and their changes is available in annual data series published by the United Nations and the Energy Information Agency of the U.S. Department of Energy. With all of these qualifications in mind (and hence always preferring rounded figures) I will use the 1800–2000 series of primary energy consumption (with the year 2008 added for the latest comparison)—including coals (anthracites, bituminous varieties, and lignites), hydrocarbons, biofuels, and primary (hydro and nuclear) electricity—summarized in the appendix in order to trace the grand global energy transition from traditional biofuels to fossil fuels.

Comparing the spans of individual energy transitions cannot be done without defining their onsets and progressive milestones. Given the antiquity of coal's small-scale localized extraction it is particularly necessary to impose a meaningful threshold to begin that particular count. Choosing 5% of the total global fuel supply as the beginning of a transition period would mean that the transition from biofuels to coal got underway by about 1840. The first conclusion of this global quantification is that the relative importance of biofuels had not changed dramatically during the first half of the nineteenth century (it was still nearly 95% of the fuel total by 1840) but it began its accelerated decline after 1850: By 1860 the share of biomass fuels fell below 85%, by 1880 it was just above 70%, by 1890 it was less than two thirds, and although we will never be able to pinpoint the date, it is most likely that sometime during the latter half of the 1890s fossil fuels (i.e., overwhelmingly, coal) began to supply more than half of all energy derived from the combustion of fuels.

Contrary to a commonly held impression that the nineteenth century was the era of coal, on the global scale and in its entirety, that century still belonged very much to the wooden era. Between 1800 and 1900 cumulative combustion of biofuels added to roughly 2.4 YJ compared to less than 0.5 YJ of fossil fuels, which means that biomass provided no less than 85% of all of the century's fuel energy. For most of the nineteenth century coal was the only fossil fuel replacing biofuels: Even by the century's end coal accounted for about 95% of all fossil energies. Globally, coal began to supply more than 5% of all fuel energies around 1840, more than 10% in the early 1850s, more than a quarter of the total by the late 1870s, and one half by the beginning of the twentieth century (see Figure 2.12).

Bituminous coals and lignites reached the highest share of the global fuel consumption, at about 55% of the total, during the century's second decade. Even though coal's importance declined to less than 50% of all fuel energies by the late

Figure 2.12 Fisher-Pry plot of the global primary energy transition from biomass fuels to coals, hydrocarbons, and primary electricity, 1800–2010. Data points calculated from statistics in UNO (1956 and 1976) and BP (2009). The most remarkable phenomenon is the post-1970 stasis of all fossil fuel shares.



1940s, the fuel remained the world's most important source of fossil energy, and hence the leading primary fuel, until 1964 when its contribution was surpassed by crude oil. By 1970 coal and crude oil supplied, respectively, about 30% and 40% of all fuel energy, by 1980 the relative gap had widened marginally to roughly 29% and 41% and by the century's end the two fossil fuels provided, respectively, about 25% and 37% of all fuel energies (Figure 2.14). Recall that all of these comparisons exclude the non-energy products and hence the oil shares presented here are lower than those calculated (commonly but inaccurately) by using gross energy content of crude oil.

But because coal's declining relative importance was accompanied by a steady increase in its absolute production—from about 700 Mt of bituminous coals (including a small share of anthracite) and 70 Mt of lignites in 1900 to more than 3.6 Gt of bituminous coals and nearly 900 Mt of lignites in the year 2000, or a nearly six-fold increase in mass terms and a more than four-fold multiple in energy terms—coal ended up indisputably as the century's most important fuel. Biofuels still supplied about 20% of the world's fuel energy during the twentieth century, coal accounted for about 37%, oil for 27%, and natural gas for about 15%. Looking just at the shares of the three fossil fuels, coal supplied about 43%, crude oil 34%, and natural gas 20%. This indubitable conclusion runs, once again, against a commonly held, but mistaken, belief that the twentieth century was the oil era that followed the coal era of the nineteenth century.

Coal was in a big lead during the first half of the twentieth century (its energy content accounted for half of all fuels and 80% of all fossil fuels), crude oil in its second half (35% of all fuels, more than 40% of fossil fuels)—but in aggregate coal ended up significantly (about 15%) ahead of crude oil, roughly 5.2 YJ vs. 4 YJ. This means that even when using the total energy content of globally produced crude oil (including all non-energy applications) coal would either just edge out liquid hydrocarbons or, allowing for the inherent uncertainties in converting coal to common energy equivalents, the twentieth-century's cumulative extraction of the two fuels would be basically equal.

As already explained, when comparing the progress of individual energy transitions I begin the count once a fuel or a prime mover had surpassed a marginal share of an overall market and reached 5% of the total production or capacity, and I then trace approximate time spans needed to reach major milestones. For the fuels these are reaching 10%, 15%, 20%, 25%, 33%, and 40% of the overall supply in energy terms. Comparing the time spans for the three successive fuel transitions reveals some remarkable similarities. Coal replacing biofuels reached the 5% mark around 1840, it captured 10% of the global market by 1855, 15% by 1865, 20% by 1870, 25% by 1875, 33% by 1885, 40% by 1895 and 50% by 1900. The sequence of years for these milestones was thus 15–25–30–35–45–55–60.

The milestones for the liquid fuels displacing coal and biofuels (with crude oil reaching the 5% mark around 1915) were spaced at virtually identical intervals, as differences of about five years are not significant given the inherent uncertainties in the total energy count: 15–20–35–40–50–60 (oil will never capture 50% of the total fuel market). Finally, the substitution of liquid and solid fuels by natural gas (with methane reaching 5% of the global fuel market by about 1930) has a shorter sequence of 20–30–40–55 as the fuel has yet to reach 33% of the total. There is, once again, a notable similarity to the coal and oil sequence, but natural gas has taken significantly longer to reach 25% of the overall market, roughly 55 years compared to 35 years for coal and 40 years for oil. And the intervals for oil and natural gas transitions change little if they are counted only as the share of the fossil fuel substitutions (leaving the biofuels out): They become, respectively, 10–20–30–35–50–55 and 20–30–40–45.

From a purely statistical point of view a set of a mere three sequences does not provide any foundation for conclusive generalizations about the tempo of global energy transitions—but, at the same time, a remarkable similarity of the three outcomes cannot be dismissed as a mere coincidence, particularly given the fact that the substitutions have involved three very different kinds of fuels that serve identical, or similar, final consumption niches but whose extraction, distribution, and conversion require very different techniques and infrastructures. And no less significant is a clear absence of any indication suggesting an accelerating progress of later transitions: If anything, natural gas has had a more difficult time of reaching the milestones previously claimed by both solid and liquid fossil fuels. At the same time, it is also necessary to take into account the absolute quantities involved: As the global fuel production increases, it is more challenging to replicate the same relative rise in absolute energy terms.

As coal extraction rose from 5% to 25% of all fuels (between 1840 and the late 1870s), that increase required adding on the order of 250 Mt of coal, or less than 7 EJ of energy; the same increase of the total fuel market share for crude oil (between 1910 and 1945) called for adding extraction of some 300 Mt of oil, or about 11 EJ of energy, while the ascent of natural gas from 5% to 25% of global fuel production took place mostly during the rapid post–WWII expansion of global energy demand (between 1940 and 1990) and it entailed adding more than 70 EJ of energy, an order of magnitude more than during coal's rise a century earlier. Vastly increased absolute size of today's energy demand means that—even with considerably greater technical and organizational means at our disposal and even in the cases where resource availability is not a constraint—it is much more challenging to develop a new source of primary energy supply to the point where it can start making a real difference (10–15% of the total market) and then carry on to elevate it to a truly major role.

An obvious question to ask is: "Would a clever statistical analysis reveal some definite, generally applicable, rules or patterns governing the transition process?" During the late 1970s, as a part of his research at IIASA, Cesare Marchetti, asking this very question, looked for a general model describing primary energy substitutions and he found it by applying the Fisher-Pry model (Fisher & Pry, 1971) to the market shares of successively introduced fuels or primary forms of electricity. The model was originally developed to study the market penetration of new techniques and it assumes that many technical advances are essentially competitive substitutions, that once they capture at least a few percent of their respective markets they will proceed to completion and that the rate of fractional substitution is proportional to the remainder that is yet to be substituted.

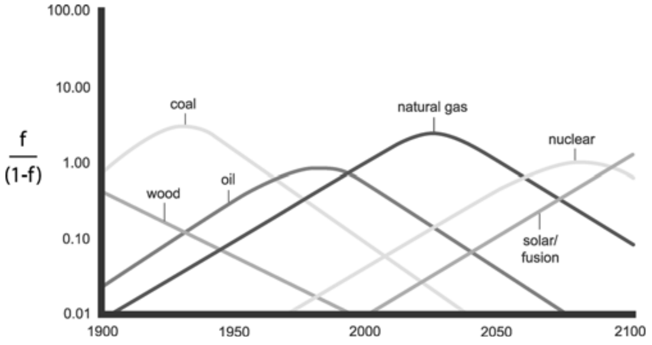
Because the adoption (market penetration) of technical advances tends to follow a logistic curve, all that is needed is to calculate the market fraction (f) of a new technique and then express it as f/1-f—and when that function is plotted on a semi-logarithmic graph it will appear as a straight line, making it possible to make apparently highly reliable medium- to long-range forecasts of technical advances. This method was developed to deal with simple two-variable substitutions and the original paper includes such examples as synthetic vs. natural fibers, plastics vs. leather, open-hearth furnaces vs. Bessemer converters, electric arc furnaces vs. open-hearth steelmaking, and water-based vs. oil-based paints.

Marchetti was impressed by "the extraordinary precision" with which the often not-so-precise data could be fitted into straight lines, but in order to use this approach for primary energy substitutions where more than two sources are in competition he could not calculate a specific fraction merely as the difference to one of the sum of the others. In the earliest stages of the substitution process there are just two competitors (coal vs. biofuels), but in later stages there will be as many as six on the global level (biofuels, coal, oil, natural gas, hydro electricity, nuclear electricity). In his first paper (Marchetti, 1977) he presented what became an often-reprinted historical evolution of primary energy sources for the world beginning in 1850 and boldly extended to 2100.

Marchetti (1977, p. 348) chose to interpret his plots in the most enthusiastic fashion, claiming that "The whole destiny of an energy source seems to be completely predetermined in the first childhood . . . these trends . . . go unscathed through wars, wild oscillations in energy prices and depressions Final total availability of the primary reserves also seems to have no effect on the rate of substitution." Two years later, in a longer report, he marveled how the penetration rates remained constant during the first three quarters of the twentieth century despite such major perturbations as wars and periods of both economic stagnation and rapid growth. This led him to conclude that "it is as though *the system had a schedule, a will, and a clock*" and that it is capable of reabsorbing all perturbations "elastically without influencing the trend" (Marchetti & Nakićenović, 1979, p. 15).

To say, as Marchetti did, that it is the system which is making the decisions is, of course, an unabashed case of determinism: Any attempts to change the course of energy transitions would be futile because humans are not decision makers, they are, at best, only optimizers. These conclusions appeared to be well supported by the semi-logarithmic f/(1-f) plots of global primary energy substitutions and the approach seemed to provide an uncommonly reliable long-range forecasting tool (Figure 2.13). But even at that time a closer look revealed that unruly realities do not quite fit such smooth deterministic patterns, and a few years before Marchetti published his findings several powerful forces began to affect the global energy system in unprecedented ways. Three decades after Marchetti's original publications it is obvious that his conclusions were excessively deterministic and that the system's dynamics can be, and have been, greatly influenced by human decisions and actions.

Figure 2.13 Marchetti's clock-like model of global primary energy substitutions, 1900–2100. The category solar/fusion refers to the combination of solar energy conversions and nuclear fusion: Marchetti had to posit its steady post-2000 ascent in order to make up for the anticipated continuing declines of coal and oil extraction. In reality, solar contributions remain negligible and there is no nuclear fusion (and no prospect for its pre-2050 commercial diffusion). Based on Marchetti (1977).



Marchetti's original analysis did not include hydroelectricity, after nearly 130 years still the world's most important source of primary electricity, whose absolute annual production was surpassed by nuclear fission for only two years (2001 and 2002). By 2008 hydro generation was, once again, about 15% higher. That was a notable omission, but its actual impact was marginal because that source (after expressing electricity simply in terms of its thermal equivalent, i.e., 1 Wh = 3.6 kJ) had amounted to less than 1% of the global primary energy supply until the early 1940s and to no more than 2.5% during the first decade of the twenty-first century.

In contrast, Marchetti's reliance on highly incorrect (indefensibly low) estimates of global fuelwood consumption led him to conclude that the worldwide combustion of wood will decline to less than 1% of the total primary energy supply before the mid-1990s. In reality, in 2000 traditional biofuels (leaving aside crop-derived ethanol and biodiesel) supplied at least 10% (and most likely close to 12%) of the world's primary energy, and by 2010 their share was still no less than 8–9%, that is, still more than energy supplied by nuclear electricity generation (but I hasten to add that this comparison is correct only in gross energy terms; in terms of useful energy, nuclear electricity was ahead, as its conversion efficiencies are obviously superior to those of burning biomass).

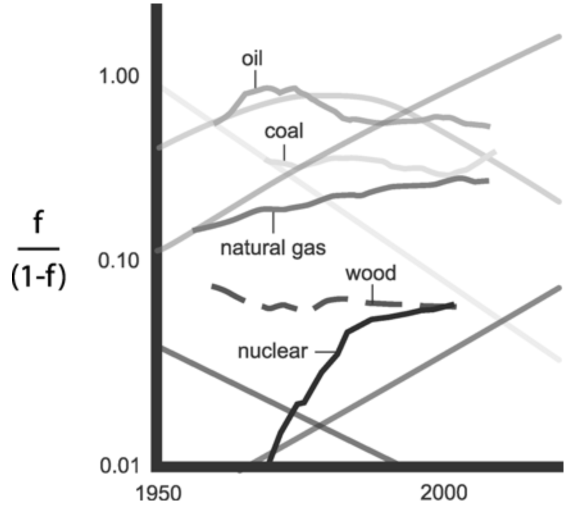
Most importantly, Marchetti's application of the substitution model to energy transitions replicates well only two major realities: the slow ascent of coal, the fuel's relative peak and pre-1970 decline; and crude oil's pre-1970 rise to become the most important fossil fuel. Everything else has been a failure. Most notably, that overly mechanistic/deterministic application was quite incapable of capturing the post-1970 departures from the expected tracks when the trend for coal and oil was mostly sideways rather than down, when natural gas continued to gain at a considerably slower pace than expected, and when nuclear electricity came close to the anticipated share by an entirely unforeseen route (see fig. 2.12).

The two rounds of OPEC's large price rises (1973–1974 and 1979–1981) triggered these shifts, but other factors contributed as the newly set trends persevered during the periods of both very high and very low oil prices. The two price rises, coming after generations of very cheap oil, slowed down the growth of global energy demand and stopped the growth of oil production for 15 years (1979–1994). But once the global oil consumption reached its relative peak (at about 46% in 1979), its subsequent decline was much slower than the retreat that was to be expected as a mirror image of its pre-1979 ascent. At the same time, the post-1975 natural gas extraction had also slowed down while coal production continued to grow more vigorously than expected. As a result, by the late 1980s, just a decade after Marchetti began to promote his deterministic model, his prediction of oil and coal shares in global energy consumption was significantly below their actual levels.

By the century's end this disparity had only increased, and it widened even more during the first decade of the twenty-first century. Oil's slower decline is not surprising given the combination of extensive use of refined products in transportation in affluent countries and of a recent rapid rise of automobile ownership in modernizing countries in Asia, above all in China and India. Coal's persistence and a significant gain of market share have been due above all to the fact that China and India have been rapidly expanding their coal extraction and that the United States (and other affluent countries) continue to rely on coal for their electricity generation.

As a result, by 2008 crude oil supplied just over 30% of the world's primary commercial energy needs, 20% above Marchetti's prediction of 25%, and the differences were much greater for coal and natural gas. Coal's 2008 share was about 29%, coming close to rival oil's share and being far above the 5% mark expected by Marchetti's clock: At that level coal's annual global output would be just over 20 EJ while the actual output in 2008 (140 EJ) was seven times larger. And natural gas delivered about 23% of the world's primary energy, far below Marchetti's 60% expected for 2010 (Figure 2.14). Combination of much lower growth of per capita energy needs in Europe and North America (with some countries actually experiencing no growth), continued efficiency gains, and the need for costly infrastructural development for LNG imports (see the first chapter) explains that slower ascent.

Figure 2.14 Comparison of primary energy shares forecast by Marchetti's model with actual values, 1950–2010. Differences for coal and natural gas consumption are particularly large, and the model is a complete failure as far as biomass energies are concerned: It has zero wood consumption by the mid-1990s while the actual share was about 10% and the gross energy value is about as large as the combined annual use of all energy in Japan, Germany, and France.



Only nuclear electricity generation now claims (when converted by using the prevailing conversion efficiency of fossil-fueled electricity generation, i.e., roughly three times its thermal equivalent) the share expected from the substitution model (about 6% of the total primary energy supply between 2000 and 2008)—but the route to this point was quite unlike Marchetti's predicted rise. During the 1970s and the early 1980s nuclear contributions rose much faster than anticipated but then, as the U.S. plant orders ceased after 1978, as European programs were abandoned or slowed down, and as only Japan, China, and India continued to build nuclear reactors, the nuclear share first reached a plateau and since 2000 it has actually declined rather than ascended. Finally, there are no signs of a smooth ascent of the "solar/fusion" category Marchetti posited for the twenty-first century: In 2010 there was no fusion-generated electricity (and no prospect of it for decades to come) and PV electricity generation was quite marginal.

There is only one possible conclusion: The internal clock that was to keep primary energy sources on schedule as they enter and exit the global fuel and electricity supply has turned out to be highly unreliable, with every one of the five trends charted by Marchetti departing significantly from the expected course by 2000, and even more so by 2010. Since 1970 the system has not behaved in a predetermined manner beyond anybody's control but has responded to an unprecedented concatenation of economic, technical, and social realities that have, once again, invalidated the merit of simplistic deterministic models. The only part of Marchetti's analysis that remains correct is the conclusion regarding the extreme slowness of the substitutions, with about 100 years needed to go from 1% to 50% of the market, a span that he called the time constant of the system. This fact has very important implications for the future of the world energy system.

Prime mover transitions are much harder to quantify and the transition from animate labor to water wheels, windmills, and steam engines presents a particularly great challenge. The main reason is the absence of reliable basic statistics that makes it necessary to resort to cumulative assumptions. Available estimates of global population totals differ by nearly 40% even for the year 1800 and the disparity is still almost 15% for 1900 (USCB, 2009). Child labor was common in all preindustrial societies as well as during the early periods of industrialization and this reality affects the estimates of economically active population. Long labor days were common in all traditional agricultures during planting, transplanting, and harvesting, but relatively long periods of low activity followed during post-harvest season. This reality complicates the estimates of typical labor burden. And highly approximate assumptions must be made regarding the average power of useful labor that depended not only on gender and age but also on nutrition and overall health.

Similarly, power of draft animals also depends on their sex, age, health, experience, endurance, harness, and soil and terrain. Steady pulls amount to about 15% of body mass for equines and 10% for other draft animals at speeds ranging typically just around 0.7 m/s for oxen and about 1 m/s for horses. These rates result in power of 300–500 W for smaller and 500–800 W for larger animals. Even draft horses in traditional societies did not average one horsepower (745 W), and if a weighted mean (considering the preponderance of weaker bovines) was around 500 W, a common draft animal worked at a rate of seven (six to eight) adults.

But the need for multiple assumptions does not prevent us from arriving at correct order-of-magnitude quantities even for the societies where there is virtually no reliable statistical information. I have calculated the maximum conceivable share of water power during the late Roman Empire by assuming high numbers of working water wheels (about 25,000 mills), very high average power per machine (1.5 kW), and a high load factor of 50% (Smil, 2010a). These assumptions result in some 300 TJ of useful work while the labor of some 25 million adults (at 60 W for 300 eight-hour days) and 6 million animals (at just 300 W/head for 200 eight-hour days) added up to 30 PJ a year, or at least 100 times as much useful energy per year as the work done by water wheels. Consequently, even with very liberal assumptions water power in the late Roman Empire supplied no more than 1% of all useful energy provided by animate exertion—and the real share was most likely just a fraction of 1%.

On the global scale the inanimate prime movers (except for sails, whose overall energy contribution is hard to quantify) were thus, at best, marginal sources of power during antiquity, and the situation did not change substantially until the nineteenth century. My approximate calculations indicate that by 1850 draft animals supplied roughly half of all useful work, human labor provided as much as 40%, and inanimate prime movers delivered between 10% and 15%. By 1900 inanimate prime movers (dominated by steam engines, with water turbines in the second place) contributed 45%–50%, animal labor provided about a third, and human labor no more than a fifth of the total. By 1950 human labor, although in absolute terms more important than ever, was a marginal contributor (maximum of about 5%), animal work was down to about 10%, and inanimate prime movers (dominated by internal combustion engines and steam and water turbines) contributed at least 85%, and very likely 90%, of all useful work.

This indicates a fairly orderly transition on the global scale, with inanimate prime movers increasing their share of useful work by nearly 10% a decade between 1850 and 1950. After they reached 10% share in 1850 it took them 30 years to go to 25%, then about 20 years to provide half of the total, 30 years to get to 75%, and some 20 years to supply 90% of all useful work. If these estimates are used in a standard binary Fisher-Pry substitution model of inanimate prime movers displacing animate work there is an excellent fit for nearly 150 years beginning in 1850: Only the most recent reality departs (although not dramatically) from the model's expectations, as animate labor still provided at least 4–6% of all useful energy in 2000 rather than a maximum of 2% indicated by the f/(1-f) trend.

In the absence of even approximate information regarding the total capacities of water wheels and windmills in eighteenth-century Europe, the Americas, and Asia, as well as the total capacities and load factors of early steam engines working on those continents, it is impossible to pinpoint the time when the contribution of steam engines surpassed the useful work of the two long-established inanimate prime movers: The most likely decade was the 1830s. Steam engines were the world's sole fuel-converting commercially deployed inanimate prime mover for 150 years, between the 1710s and 1860s (when Otto began selling his stationary horizontal internal combustion engines) and they remained the world's leading mechanical prime mover for nearly a century. By 1930 they still powered nearly all trains and more than 80% of all ships and supplied most power in industrial enterprises, but they were already gone from electricity generation. And although steam engines were deployed in field work (above all in heavy plowing), agricultural transition from animate to inanimate prime movers took off only after 1900.

Even in the richest countries the transition from draft animals to internal combustion engines (either tractors with a variety of field implements or self-propelled machines, mainly various harvesters and combines, as well as trucks used to deliver farm supplies and transport harvested crops, milk, and animals) took more than half a century when measured by the numbers of remaining working horses, but it took place much faster when looking at the aggregate power of the two kinds of prime movers. The first gasoline-powered tractors were built around 1890—John Charter in Sterling, Iowa, in 1889 and John Froelich, also in Iowa, in 1892 (Williams, 1982)—but by 1910 there were still only some 1,000 machines. Aggregate tractor power had surpassed that of horses and mules during the early 1920s and reached 90% of the total by 1950. In Europe the mechanized field work became common only after World War II, in China only during the 1970s, in India during the 1980s.

Perhaps nothing illustrates better the gradual process of agricultural mechanization than the fact that in the year 2000 low-income countries, with some 80% of the world's population, had less than 30% of the world's 27 million tractors (compared to nearly 20% in the United States alone) and, given much larger capacities of U.S. machines (the largest ones now rate in excess of 300 kW, i.e., more than 400 hp), an even lower share of total tractor power. My approximate calculations show that even in 1950 the useful work done by the world's 400 million draft animals and by tractors were roughly equal, and that in the year 2000 field and transport service provided by some 500 million animals still supplied perhaps as much as 20% of all (excluding human) agricultural labor. But a transition within this transition, from gasoline-powered to predominantly diesel-powered tractors, was fairly rapid: Diesel tractors were introduced in the early 1930s and by the 1960s all more powerful machines were diesel-powered; small tractors, including the hand-guided two-wheelers (rotary tillers) used in the monsoonal Asia remained powered by gasoline.

There is no simple way to quantify the transition to mobile (automotive and truck) internal combustion engines because these vehicles displaced a variety of transportation modes (ranging from porters to canal barges) and specialized conveyances, some powered by human and animal muscles (litters and wheelbarrows, carts and wagons), others by wind (sail ships) and steam (steam ships and trains). Moreover, car ownership did not necessarily eliminate all of the previous uses: In many countries (most notably in Japan and in many EU nations) high levels of car ownership coexist with a widespread use of public transport.

But we can time three important shifts away from steam engines: to steam turbines in thermal electricity generation, to diesel engines in shipping, and also to diesel engines on railroads. The first transition was a rapid one because the turbines were accepted as a superior choice in less than two decades after their introduction. The last major U.S. coal-fired station with steam engines (16 massive Westinghouse-Corliss machines) was New York Edison's East River in 1902, the last British installation of that kind was London's County Council Tramway power station in Greenwich completed in 1905 (Dickinson, 1939).

Conquest of marine shipping by diesels can be dated precisely, from *Selandia* in 1911 to the *Liberty* ships of World War II whose production ended in 1945: Many steam engines continued to work well into the 1950s, but by that time all new large ships were diesel-powered. Prime mover transition on railroads was not that straightforward: Diesel locomotives began to be introduced in both Western Europe and the United States during the late 1920s. In the United States they captured half of the market by 1952 and accounted for 90% of all locomotives by 1957; a Fisher-Pry plot shows slightly bent lines because of a relatively slower substitution progress during the war and a very rapid rate of change after 1950 (Sharif & Kabir, 1976). Except for a few isolated cases steam locomotives were gone from the U.S. railroads by 1960 and in Western Europe about a decade later (only in China and India many of them served into the 1990s)—but unlike in the United States, some countries (Japan, France, Germany, Russia) electrified most of their tracks and hence both their fast passenger trains and heavy freight trains are powered by electric motors.

This means that large marine diesels needed about 40 years to move from pioneering designs to a near-complete dominance of that important transport niche. Similarly, where the transition on railroads was solely, or largely, from steam to diesel engines, its duration was 35–45 years from the first models to near-complete dominance. The fastest substitution of draft animals by tractors took place in the United States, with 30 years from the first introduction (in the early 1890s) to more than 50% of total power (in the early 1920s), but another 30 years were needed to bring that share above 90%. In Western Europe the spans from introduction of tractors to their near-complete dominance were about 60 years and the transition has yet to be accomplished in many Asian and African countries.

Chapter 3

NATIONAL TRANSITIONS: COMMONALITIES AND PARTICULARITIES

All socioeconomic phenomena have their national specificities and often also unrepeatable peculiarities, but simple binary approaches are often surprisingly powerful tools for taking a closer look at such differences. There is no need to succumb to any simplistic environmental determinism in order to realize that the fortunes of modern societies have been shaped to a large degree by the fundamental differences between the tropical environments (their climates, soils, and vegetation) and their temperate counterparts (Sachs, 2001). Similarly, a simple division between the rich nations (other labels, including affluent, high-income, modern, or even post-modern may be even better, but I prefer not to use the term developed) and the poor countries (low-income, modernizing, industrializing; again, I prefer not to use the term developing) captures a great deal of fundamental differences in terms of many socioeconomic achievements (ranging from per capita income to infant mortality and from access to education to political freedoms).

But such convenient and often-used shorthand divisions also hide a great deal of intragroup variability: The true tropics (year-round humid and rainy) differ greatly from seasonally dry tropical regions, and, as comparisons of the UNDP's Human Development Index (HDI) illustrate so well, similar levels of economic advancement (or lack of it) often hide substantial differences in actual quality of life. Just a single notable example contrast illustrates this disparity: South Korea and Saudi Arabia have nearly identical GDP/capita but at 0.928 South Korea's HDI is far ahead of the Saudi level of 0.835 (UNDP, 2009). Analogically, national patterns of energy transitions show significant variations among countries whose economic achievements are very similar (Smil, 2008).

There have been two basic patterns of economic progress that broadly correspond to two principal paths of grand energy transitions and to two prevailing modes of typical affluence. The first one can be simply labeled as early innovators whose eventual attainment of high average per capita energy use created the first affluent societies. This (relatively homogeneous) category encompasses leading economies of Western Europe and the United States and Canada but it, too, contains some notable outliers. In England, Wales, and Scotland the grand energy transition from biofuels to fossil fuels had begun already during the sixteenth century and was nearly complete by the end of the eighteenth century—while other early European innovators had accomplished most of this process only during the nineteenth century. In contrast, differences in reliance on the two principal preindustrial inanimate prime movers were much less consequential as even relatively common use of water wheels (in France and Germany) or windmills (in Holland and England) was greatly surpassed by animate labor.

The much larger group of late innovators includes all countries whose high (or at least very substantial) dependence on non-fossil energies lasted until the second half of the twentieth century and where the rates of fuel and prime mover substitution and the consequent lifting of average quality of life above the subsistence level have proceeded at generally much faster rates than in the first group, often compressing the process of energy transition from biofuels to fossil fuels into just two generations. Again, this group has its outstanding performers (South Korea, post-Mao China), relative laggards (India, Indonesia), and recalcitrant cases (Pakistan, Bangladesh). In between these two modal groups are the countries that began to modernize during the nineteenth century but that had attained higher standard of living only after World War II: Japan and Russia are perhaps the most notable examples in this category.

I will trace in some detail energy transitions in eight countries. Britain was the first society to accomplish the epochal energy transition from biomass to coal, more recently it had pioneered nuclear electricity, and it has been a vigorous developer of offshore hydrocarbons. France's nineteenth-century transition was rather typical of the continental experience but the country's bold development of nuclear energy sets it apart from all other affluent nations. The Netherlands had a precociously "modern" economy energized by a remarkable seventeenth-century energy transition, and it was able (after first reverting to a more common energy transition pattern) to chart once again a special course thanks to the discovery of one of the world's largest natural gas fields. The United States is an energy superpower richly endowed with fossil fuels—but it is also by far the world's largest energy importer. Japan and China, two very different Asian powers, share a common trait of compressing the modernization process into remarkably short periods. And Russia and Saudi Arabia, the two new energy superpowers, now have decisive roles in supplying the world with oil and gas.

Tracing these transitions will make it clear that the British experience was entirely *sui generis* (its lessons are quite different from the French or the Dutch process), and that the United States rose to affluence along a trajectory that was very different from the European quest for high-energy modernized society. China's belated quest for modernity has been energized by one of the world's most idiosyncratic energy transitions, and Japan has the distinction of being the only one of the world's five largest economies to be almost entirely dependent on energy imports. And as different as Russia and Saudi Arabia undoubtedly are, their energy transitions had shared some (and not necessarily desirable) traits.

These eight case studies also cover a substantial (and hence highly representative) share of the current global economic power and energy use: Combined population of the examined nations is about 30% of the world total, but their aggregate economic product is now equal (in purchasing power parity terms) to 50% and their energy consumption adds up to 55% of the global total.

But this selection, as representative as it may be, begs at least two obvious questions. The first one is why not to include Germany, a great pioneer of technical advances in general and of energy innovations in particular, and the EU's largest economy? And the second, why not India, the world's second most populous nation and now also the world's fourth-largest (in terms of purchasing power parity) economy? The first deliberate omission is largely due to statistical complications. There was no united Germany during the earliest stages of the grand energy transition of the seventeenth to the early nineteenth century, and the German Empire had different borders (and hence incomparable populations and GDP outputs) at the time of its establishment in 1871 (after the defeat of France and annexation of Alsace-Lorraine), in 1918 (after its defeat in World War I), in 1939 (after its annexation of Austria, Bohemia, Moravia, and a large part of Poland), in 1945 (after its defeat in World War II deprived it of all territories east of the Oder), between 1945 and 1990 when it was divided into two countries, and after October 1990 (when the two states were reunited). Navigating through these shifts is a difficult task even where the most basic statistics are concerned.

Territorial changes are not a problem in India's case because the country's epochal energy transition from biomass to fossil fuels got really underway only after the partition of British India and the creation of a new independent Indian state in 1947. I excluded the country from a more detailed historical examination not only because its transition to modern energies is of a relatively recent origin (with large parts of rural India perpetuating the traditional dependence on biomass fuels and animate labor for mechanical power)—but also because it shares a number of its basic features (very large rural sector, delayed urbanization, use of crop residues for fuel in extended arid and deforested areas, high dependence on coal, large hydropower potential, late onset of hydrocarbon imports) with the process that has been unfolding in China.

I have also deliberately weighted my choice toward large economies: Britain was the largest Western economy until it was surpassed by the United States in the early 1870s—Maddison (1995) puts the British GDP at less than 2% above the U.S. total for 1870—and the United States has been the global leader ever since. China is now number two (in terms of purchasing power parity), Japan number three, Russia number six, and France, Europe's second-largest economy, number eight. The coming energy transition away from fossil fuels will be of an unprecedented magnitude and hence the experiences of the six large economies are much more relevant than the performances of small (be it in territorial or population sense) nations, and particularly those small countries that are fortuitously endowed with abundant resources (be it Norway, Kuwait, or Brunei). In such economies energy transitions can happen very rapidly and those experiences have little relevance for nations with large populations, large territories, and the requisite needs to develop extensive infrastructures (be it the United States, Russia, or China).

EUROPEAN EXPERIENCE: BRITAIN, FRANCE, AND THE NETHERLANDS

Why an offshore island country became the world's first society to undergo the process of industrialization energized primarily by coal has been one of the most fascinating, and most recurring, questions of historical analysis, and I have already referred (in the first chapter) to some of the arguments advanced as explanations. This section's modest aim is merely to quantify the process of this primordial English, Welsh, and Scottish biomass-to-coal transition, follow its consequences as Britain lived on an extended coal plateau for nearly three centuries, and then analyze those post–WWII developments that have profoundly changed the country's energetic basis and hence its very economic foundations.

Tracing the earliest history of Britain's energy transition from wood to coal is a task that has been made relatively easy thanks to several detailed and revealing inquiries into this subject, including Nef (1932), Flinn (1984), Mitchell (1984), and Fouquet (2008). English coal—known and used sporadically in small manufactures for centuries—became an increasingly important heating fuel already during the first half of the sixteenth century, above all (due to its falling prices) among poorer households. But even the late Elizabethan nobility still disdained the use of coal with its sulfurous smoke, and the regal example was needed to overcome that resistance as Elizabeth's successor (James I, crowned in 1603) began to use coal in his London palace (Brimblecombe, 1987).

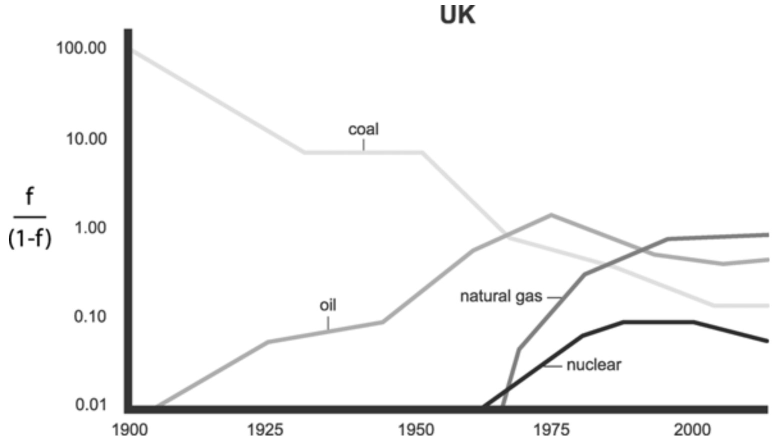
Nor was coal's use in industry a matter of enthusiastic adoption. As its price declined, coal began to be used first in manufactures that required relatively low heat supply from below (smithing, brewing, dying, and production of salt, lime, and soap). After 1610 glassmakers began to switch to coal thanks to the introduction of reverberating (heat-reflecting) furnaces that produced sufficiently high temperature. Because of a gradually rising demand, nearly all of the coalfields that later made the country the world's largest fuel producer (in the Northeast, Yorkshire, Midlands, Wales, Scotland) were opened for commercial exploitation before 1640, and fairly reliable data show annual extraction (no more than 25,000 t by 1600) surpassing 2 Mt by 1650 and reaching 3 Mt by 1700.

Quantitative reconstructions of the earliest energy transition—in the case of England and Wales this means the shift from wood and charcoal to coal during the sixteenth and the seventeenth century—can be only approximate. Warde (2007) is thus correct when he concludes that the choice of a precise date for the tipping point between the two kinds of fuel is arbitrary: His data compilation shows that coal surpassed biomass as the source of heat most likely around 1620, perhaps a bit earlier. By the middle of the seventeenth century British coal supplied two thirds of all thermal energy, by 1700 about 75%, by 1800 about 90%, and by 1850 its share was in excess of 98%. This coal supremacy lasted for another 100 years: By 1950 coal's share was still 91% and by 1960 it declined to 77%, the rate it had reached already during the first decade of the eighteenth century. This means that coal dominated the country's thermal energy use (supplying more than 75% and as much as 99% of the total) for 250 years, a period of dependence unmatched by any other nation (Figure 3.1).

Inevitably, final coal uses had seen many shifts during this long period: First came the coal combustion as a direct source of thermal energy for household heating and in manufacturing; steam engines created a new market for coal as a source of mechanical energy for stationary industrial applications. Adoption of metallurgical coke introduced another powerful positive feedback: By 1780 coke price was down by two thirds compared to 1740 and coal use for coking rose from less than 3,000 t in 1750 to 170,000 t by 1800 (Harris, 1988). The next important new market for coal was the production of town (coal) gas used for illumination. Coal consumption got its largest boost from the emergence of pressurized, and hence smaller and more efficient, mobile steam engines used after 1840 on large scales in railroad locomotives and in ship propulsion. Soon after a smaller new market emerged for non-energy uses of coal (specifically coal tar) as a feedstock for syntheses of organic chemicals, but by far the most important (and enduring) new final use of coal came during the 1880s with electricity generation.

British coal production reached its peak in 1913 (with 287 Mt) and it was reduced less by World War I than by two general strikes in 1921 and 1926.

Figure 3.1 Fisher-Pry plot of the primary energy transition in the United Kingdom, 1900–2010. Data points calculated from statistics in UNO (1956 and 1976), Hicks and Allen (1999), and BP (2009). By 1900 there was virtually no wood use and hydroelectricity has always been a marginal source and its shares are not shown. Recent hydrocarbon shares have leveled off and nuclear electricity began an early retreat.



In 1947, at the time of its nationalization (creation of National Coal Board) it was still nearly 200 Mt (197.4 to be exact) and its postwar peak in 1953 was 228.4 Mt. Rising oil and gas consumption halved it by 1980 and the coal miners' strike of 1984 marked the beginning of its end. During the strike year the total output fell to only about 40 Mt, then it had nearly recovered to the pre-1984 level but soon it began to fall again. This trend was not arrested after the industry was re-privatized in 1994: By the century's end British coal extraction was just about 30 Mt and in 2005 it was barely above 10 Mt/year.

Social dislocations of this shift were profound: At the time of nationalization in 1947 the coal industry's labor force totaled nearly 704,000 but in 1994, at the time of re-privatization, there were only about 25,000 employees (Hicks & Allen, 1999). But because the country's electricity generation has remained highly dependent on coal, and because Britain's remaining blast furnaces still needed coke, the shortfall in domestic production had to be made by increasing coal imports: In 2001 the UK's coal imports surpassed domestic output as coals to Newcastle changed from a proverbial description of a superfluous activity to commercial reality.

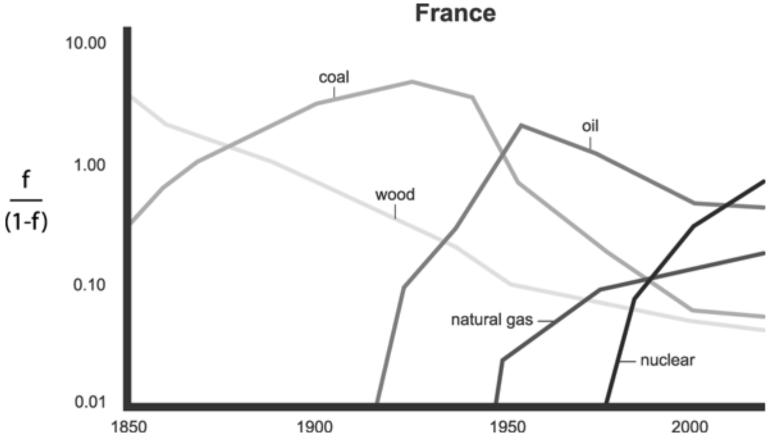
Decline of British coal mining was accelerated by the discoveries of the North Sea hydrocarbons (first natural gas in the West Sole field in 1965, then crude oil in the giant Forbes field in 1970) and by a temporary conversion of Britain into one of the world's leading producers of oil and one of the largest users of natural gas. British geologists were among the pioneers of the global search for oil and British engineers developed some of the world's earliest oilfields, particularly in Burma, part of British India (Burmah Oil Company was set up in 1886) and in Persia where in 1908 William Knox D'Arcy drilled the first Middle Eastern oilfield at Masjid-e-Soleiman and the Anglo-Persian Oil Company, the precursor of British Petroleum, was setup a year later (Ferrier, 1982). The country was thus an early, and relatively substantial, importer of crude oil and, as already noted, Britain also pioneered LNG imports.

Natural gas consumption began to make a real difference only with the development of the North Sea fields: In absolute terms it increased nearly nine-fold between 1970 and 2000 (from about 11 Gm^3 to nearly 97 Gm^3), in relative terms from less than 5% to 39% (Figure 3.1). British crude oil production rose from just 200,000 t in 1970 to the peak of about 137 Mt by 1999 (placing eighth worldwide that year, ahead of Iraq and Canada and just behind Norway) and it enabled the country to satisfy not only its own demand but to become a temporary exporter; in 2006 the declining production (76.6 Mt) slid about 7% below the total consumption (82.3 Mt). In relative terms crude oil consumption surpassed 10% of all British primary energy only in 1952 but then it rose rapidly to 50% by 1973, declined afterwards to about 35% by 2000, and rose slightly to just over 37% by 2008 (Figure 3.1).

Britain's short streams offer a limited opportunity for the development of large water projects and the contribution of hydroelectricity to the overall primary energy never rose above the negligible level (less than 0.1% by 1950)—but the country had a pioneering nuclear program with the first station, Calder Hall, commissioned in 1956 (Williams, 1980). Nuclear electricity's eventual peak contribution (in 2000) was close to 9% of all primary energy. Subsequent closure of old stations (Calder Hall was shut down in 2003) reduced its share to less than 6% by 2008. The realities of British primary energy supply at the beginning of the twentieth century thus bore very little resemblance to those inexorably scheduled penetrations that Marchetti and Nakićenović (1979) envisioned just 20 years earlier: In the year 2000 coal was at about 16% rather than at 3%, oil was at 35% rather than at a mere 1%, and natural gas was at 39% rather than around 80%; only nuclear electricity was close to the forecast share of 10%.

France, with a much larger territory than Britain, and with most of its *départements* having extensive and highly productive forests, was able (much like Germany) to rely on wood and charcoal as the principal source of heat for generations after biomass became a marginal source of energy in Britain. The best indication—based on the most comprehensive set of historical data of energy production, trade, and use (Barjot, 1991)—is that during the early Napoleonic times more than 90% of France's primary energy came from wood, that that share declined to about 75% by 1850, and that it slipped below 50% by 1875. By 1880 coal provided about 55% of all primary energy and it then dominated France's primary energy supply until the late 1950s when it yielded to imported crude oil whose share rose to as much as 68% by 1973 (Figure 3.2).

Figure 3.2 Fisher-Pry plot of the primary energy transition in France, 1850–2010. Data points calculated from statistics in Barjot (1991), UNO (1976), and BP (2009). Wood share has been declining for more than 150 years, coal's importance peaked before World War II, and determined promotion of nuclear generation has made it the single most important source of the country's primary energy, a globally unique achievement.



France, alone among the world's major economies, chose an effective response to this high level of dependence: In 1974 the government began the first large-scale (16-unit) program designed to make nuclear generation the dominant mode of the country's electricity production (Larroque, 1997–1999; Reuss, 2007). The French nuclear program began during the late 1950s with three gas-cooled reactors but in 1969 the French military mastered uranium enrichment (a key necessity for de Gaulle's independent nuclear *force de frappe* initiated in 1958) and the subsequent enlargement was based on standardized sizes of U.S. Westinghouse pressurized water reactors (PWR) that use enriched fuel. Only two sizes of these reactors, produced by Framatome (established in 1958), have been used, the most common 900-MWe unit and a larger 1.3-GW unit. The third size, rated at 1.45 GW, is now made by AREVA the company that was set up in 2001 by merging Framatome with Cogema.

By 2010 France had 59 reactors that have been strategically distributed around the country: Massif Central and Midi-Pyrénées are the only regions without them. Their total capacity is about 63 GW but because they constitute such a large part of the total installed power (nearly 80%) they cannot be used (as is the norm elsewhere) only for the base load generation and must be operated in the much more challenging load-following mode (WNA, 2009). As a result their average load factor during the years 2006–2008 was only about 79% compared to more than 91% in the United States or South Korea. Even so, French reactors now generate more than 400 TWh a year, or 75–78% (depending on the contribution by hydro stations) of all electricity, a share not matched (not even approached) by any other major economy: In 2008 only three small countries, Lithuania, Slovakia, and Belgium, had shares in excess 50%, and the next highest share for a large economy was Japan's with about 25% (IAEA, 2009).

Nuclear electricity's share of the French primary energy supply rose from 0.2% in 1965 to more than 7% by 1985 and to nearly 33% by 1990 and it has been above 35% since 1993 (peaking at just over 39% in 2005). This impressive gain has been a major factor in reducing the absolute level of French oil imports in 2008 by nearly 28% below their peak 1973 level. As in the British case, the expectations of future shares based on apparently fixed rates of market penetration proved to be far off: Marchetti and Nakićenović (1979) foresaw the French primary energy shares in the year 2000 at just 1% for coal, less than 10% each for oil and gas, and more than 80% for nuclear electricity—while the real shares were, respectively, about 5%, 37%, 14%, and 37% (Figure 3.2).

The Dutch case is so noteworthy because the country had experienced a highly idiosyncratic path to a high-energy society on two widely separate occasions. Holland, the country's key province, had undergone a very early, and a very atypical, energy transition during the seventeenth century, and I had already noted (in the first chapter) the exceptional post-1960 Dutch energy transition from coal to natural gas: Here I will take a closer look at both transformations. The Dutch Republic, and particularly the province of Holland, was one of the great pioneers of adopting fossil fuels and inanimate sources of energy, and it had done so in two rather uncommon ways, by large-scale production of peat and by an extraordinarily high reliance on wind power.

Exploitation of these resources resulted in a relatively high per capita use of inanimate energies, enabled an uncommon degree of urbanization (already more than 60% during the seventeenth century), powered the industrial development of the Dutch Golden Age, and provides the best explanation how a population of just 1.5 million people could "manage to play leading parts on almost every scene of human activities" (de Zeeuw, 1978, p. 3) and enjoy average annual energy consumption of at least 15 GJ/capita, that is, more in 1650 than India averaged in 2000. Peat, the youngest fossil fuel, was the principal source of industrial and domestic heat, and, fortuitously, every one of Holland's major cities had nearby resources that could be easily extracted and inexpensively transported. Peat's annual consumption during the seventeenth century averaged about 1.5 Mt (equivalent of about 25 PJ or nearly 800 MW) but coal and firewood were also imported and Holland's windy climate and flat landscape provided excellent conditions for harnessing wind by sails and mills.

Assumptions and simplifications are needed to estimate the aggregate output of these two prime movers and hence de Zeeuw's calculations (1978) must be seen only as revealing approximations. Some 3,000 windmills (with average power of 2.5 kW) generated less than 200 TJ (about 6 MW) and sailing ships contributed annually another 150 TJ (nearly 5 MW) of power. These are relatively small aggregates (each less than 1% of the peat's energy content) but they resulted in large savings of human and animal labor and reduced the amount of land needed for the animal feeding: Replacing the windmills would have required at least 300,000 workers or some 50,000 horses and feeding those animals would have claimed a sixth of the country's total area in addition to the existing crop fields. After the best peat deposits were depleted and shipping became more expensive due to extensive silting of shallow waterways and harbors, Holland ceased to be an exception and its energy use began to resemble that of the neighboring countries.

Although coal was mined on a small scale in the southeastern part of Limburg province since the sixteenth century, the Dutch industrialization was powered largely by coal imported from Britain and Germany (van der Woude, 2003). Large-scale commercial exploitation of Limburg coal began during the 1870s and in 1902 a new state company (*Staatsmijnen*) was added to the basin's private collieries. Domestic coal production reached the peak of about 14 Mt during the late 1930s, it fell to less than 6 Mt by the end of World War II, and then climbed back above 12 Mt during the 1950s when the competition from imported oil was making the future of South Limburg mines precarious and after 1958 outright unprofitable.

The enormous Groningen gas field (extending over about 900 km^2) was discovered near Slochteren on July 22, 1959 and the first gas deliveries came in

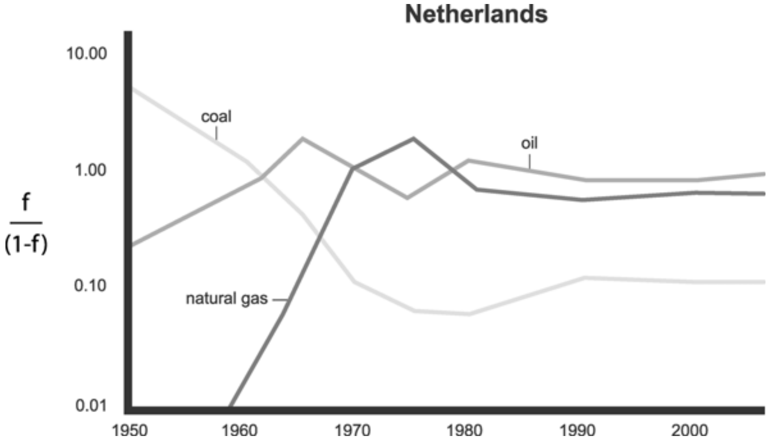
December 1963. The magnitude of this discovery—initially appraised at 60 Gm^3 but eventually raised to 2.8 Tm^3, or nearly 50 times the original estimate (Correljé & Odell, 2001)—placed the field among the rarest of all hydrocarbon resource categories, that of supergiant natural gas fields (with reserves of at least 850 Gm^3). Groningen gas had truly revolutionized the country's energy balance because even after virtually all industries and households converted to its consumption there was still plenty left for exports.

These exports' earnings made it much easier to end all Dutch coal mining and to reorient Limburg's industries. In December 1965 the government decided to phase out all of the coal mining in the Limburg province within 10 years, removing the economic basis for more than 200,000 people in one of the most densely populated regions of the country and doing away with some 45,000 mining and 30,000 related jobs. Largely successful countermeasures included subsidies for new industries and relocation of some government offices from the capital and the *Staatsmijnen* (DSM after 1967) was given a share (40%) in the Groningen's development and transformed itself into a major producer of a variety of industrial and consumer goods (DSM, 2009). Groningen gas production rose rapidly to more than 80 Gm^3 by the mid-1970s (Roels, 2001) and as a result the Dutch primary energy consumption had experienced energy transition from solid to gaseous fuels that proceeded faster than in any other country.

In 1950 coal supplied 83% of the country's primary energy and oil a bit less than 17%. In 1959, at the time of Groningen's discovery and with Rotterdam as Europe's leading oil port, the Dutch primary energy supply (in the country of just over 40,000 km^2 and about 11.5 million people) was still led by coal with about 55% of the total; crude oil delivered 43% and natural gas less than 2% of the total (UNO, 1976). Afterwards the country not only converted rapidly to the new fuel (Figure 3.3)—a shift that was further aided by the belief that the gas should be produced and sold as fast as possible before nuclear energy becomes dominant—but it also began its large-scale exports to its neighbors. Dutch natural gas exports rose from less than 10 Gm^3 in 1970 to more than 40 Gm^3 by 1980, leveled off afterwards, and by 2008 they were still close to 30 Gm^3.

Natural gas reached 1% of the country's primary energy supply in 1958 (prior to the Groningen discovery this was methane recovered from coal mines), in 1965, when the decision was made to close down all of the country's coal mines, natural gas supplied 5% of the country's primary energy—but by 1971 it rose to 50% and by 1975, with almost 46%, it was only a couple of percent behind the imported crude oil; during the same time, coal's share fell from 26% to 2.5% (the small remainder being mainly coking coal for smelting iron). After its brief peak output of the mid-1970s Groningen extraction was deliberately restricted in order to extend the field's lifetime; by 1990 more than half of Dutch gas supply came from smaller onshore and offshore fields, and Groningen's output fell to less than 30 Gm^3 by the year 2000 (Roels, 2001).

Figure 3.3 Fisher-Pry plot of the fossil fuel transition in the Netherlands, 1950–2010. Biomass and hydroelectricity make negligible contributions and nuclear fission supplies less than 5% of all electricity. Data points calculated from statistics in UNO (1976) and BP (2009). Post-1975 stagnation of fossil fuel shares is obvious.



In recent years the field has been supplying about 40% of all Dutch gas consumption, about half has been coming from smaller fields and a tenth from imports—but the natural gas share in the country's primary energy supply has remained high, 40% in 2000 and still 36% by 2008. Groningen's rapid development and the closure of all coal mines meant that after reaching 5% of the Dutch primary energy supply it took natural gas only a year to go to 10%, three years to reach 25%, and six years to reach 50%. As I will show in the following sections, it took the U.S. natural gas 20 years to go from 5% to 10% and 50 years to go from 5% to 25% and the analogical Soviet spans were, respectively, 8 years and 10 years.

U.S. TRANSITIONS: THE CONSUMING SUPERPOWER

U.S. historical statistics offer an exceptionally comprehensive basis for following almost every conceivable energy transition, be it the shifts in the composition of primary energy supply (beginning with the epochal substitution of biofuels by fossil fuels to the subsequent rise of natural gas and nuclear generation) or in the shares of mechanical energy supplied by various prime movers. Unless otherwise indicated all statistics used for the U.S. transition analyses are taken mainly from the *Historical Statistics of the United States: Colonial Times to 1970* (USBC, 1975), U.S. EIA (2009), and Schurr and Netschert (1960), and secondarily from Daugherty (1927), Hunter (1979), Hunter and Bryant (1991), and Milici (2003). The United States is also one of a few countries where we can rather accurately follow the prime mover transitions in agriculture, while other data make it possible to trace the replacement of open-hearth steelmaking by electric arc furnaces and the displacement of steam engines by diesel locomotives on the country's railways (Sharif & Kabir, 1976).

I will first look at the transitions from biofuels to coal and oil during the nineteenth century and then at the changing shares of fossil fuels. America's commercial coal mining began in 1758 with a small shipment of Virginia coal to Manhattan Pennsylvania (with bituminous coal and anthracite) and Ohio, the other two states with extraction going back to the eighteenth century, were soon joined by Illinois and Indiana. Production estimates begin in 1800, when the three states in the Appalachia mined about 100,000 t of coal (Eavenson, 1942). Coal extraction supplied 5% of the total primary energy output by 1843, nearly a century after the beginning of commercial coal mining. The subsequent rise of coal was rapid, reaching 10% of all fuel energy supply just eight years after it passed the 5% mark, 20% share in two decades, a third in about 30 years, and half in just over four decades. In 1884 coal produced more energy than wood and by 1900 the U.S. coal industry produced two thirds of all fuel energy.

U.S. commercial crude oil extraction began on a very small scale—15 barrels (about 2 t) a day from a single well—in 1859 at Oil Creek near Titusville, PA (Owen, 1975). U.S. oil extraction grew very rapidly, from less than 300 t in 1859 to about 70,000 t a year later, nearly 300,000 t in 1861, more than 700,000 t in 1870, 3.6 Mt in 1880, and close to 9 Mt in 1900. By that time Pennsylvania's production—mainly from the country's first giant oilfields in Bradford (discovered 1875) and Allegany (working since 1879)—was supplemented by extraction from California's Brea-Olinda (since 1884) and McKittrick (since 1887) and soon afterward (1894) from Corsicana field in Texas. But oil's rapidly expanding extraction remained a minuscule part of the country's fossil fuel supply: In 1860 it provided 0.6% of all energy derived from fossil fuels, its share rose to 1% in 1870 and 4.4% by 1880 and then, as natural gas began to make its first inroads, it fell to about 3.1% by the century's end.

But because until the early 1880s wood was the country's leading fuel (and because it still provided just over 20% of the total by 1900), oil's contribution to the total primary energy supply remained marginal, rising from a mere 0.1% in 1860 to 0.3% in 1870, 1.9% in 1880, and 2.4% in 1900. U.S. oil production intensified right at the beginning of the twentieth century as new giant oilfields (California's Kern River, discovered in 1899, and Midway-Sunset in Texas, with its famous Spindletop gusher, drilled in 1901) began their production (Linsley, Rienstra, & Stiles, 2002). Discovery of the state's biggest field, the East Texas in 1930 (followed by the West Texas in 1936) led to supply glut and the enforcement of production quota by the Railroad Commission of Texas, whose monopoly lasted until 1971 (RCT, 1991).

In 1900 the United States had only seven giant oilfields, by 1925 there were 75, by 1950, 220. Consequently, there were no physical limits on extraction and it rose rapidly, driven by the demands of mass car ownership, expansion of shipping, use of oil for industrial and domestic heating and for electricity generation, and by the wartime effort: World War II was the first major conflict in which the U.S. forces were energized primarily by refined oil products. In relative terms oil supplied 7.1% of America's fossil fuels (and 6.1% of all primary energy) in 1910, the two shares rose to 12.5% and 11.2% by 1920, and to 20.6% and 18.5% by 1925. Crude oil began to supply more than a quarter of America's primary energy by 1933 and more than a third by 1948.

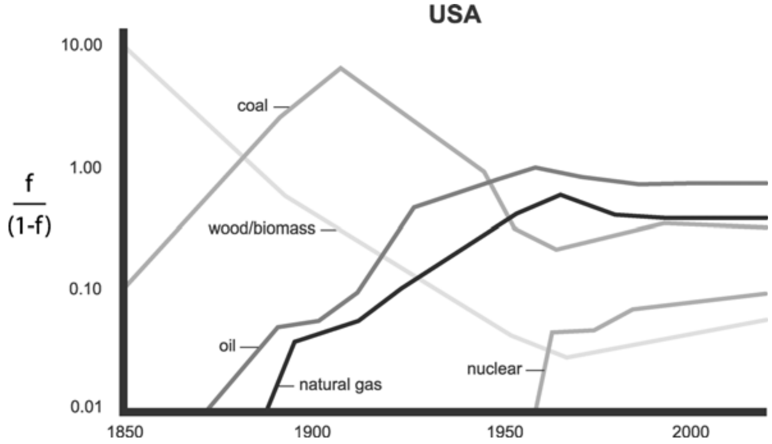
After World War II the pace of new major oil discoveries slowed down dramatically, with Alaska's North Slope being the only giant find of the 1960s. The U.S. oil extraction peaked in 1970 with about 535 Mt and afterwards the country has become increasingly more dependent on oil imports—but it has become the world's largest crude oil importer only because its per capita consumption of the fuel is so extraordinarily high: It remains the world's third-largest producer and if it were to consume refined oil products at the French rate (average annual crude oil supply of 1.4 t/capita rather than 2.9 t/capita) it could reduce its 2008 crude oil imports by nearly 80%, well below the current Japanese level!

Obviously, the downslope of the extraction curve has not mirrored its ascent: Hubbert's (1956) often-cited production curve anticipated annual production of 1.2 billion barrels in 2000, but the actual rate was 2.8 billion barrels, nearly 2.5 times higher, and the output in 2008 was almost 70% above the rate forecast for that year. And because the declining domestic production was promptly supplemented by increasing crude oil (and refined products) imports, there was at first no, and later only a slight, decline in terms of the relative contribution of liquid fuels to the U.S. primary energy supply: The share was about 43.5% in 1970, 43.6% a decade later, and in 2008 it was still 38.5%.

Extraction of natural gas could not begin on a larger scale without long-distance pipelines, but once the fuel's share reached 5% of all primary energy (in 1924) it expanded nearly as fast the oil production: Just 11 years later it was at 10%, after 27 years at 20%, and in 1957 natural gas surpassed 25% of the country's primary energy production. Consumption trend was very similar and it kept rising until 1972 when it peaked at about 32.5%—but, as with crude oil consumption, this was not followed by any precipitous retreat. The fuel's share declined to just below 23% by 1990 but since that time it has been on only a slightly fluctuating plateau.

Fisher-Pry plots of U.S. primary energy consumption show a steady post-1850 ascent of coal and corresponding decline of wood use and the peak coal share (at nearly 77% in 1910) followed for the next 50 years by a decline that was almost a perfect mirror of the late-nineteenth century ascent. By 1960 coal's share was down to less than 22% but then its retreat slowed down and after reaching a low of just over 16% in 1976 it began to recover and by the century's end it stood at nearly 23%. And because wood consumption has remained fairly steady after 1960 we have a remarkable phenomenon of all sources of U.S. primary energy more or less maintaining their consumption shares for the past 50 years (Figure 3.4). The magnitude, and the importance, of these new plateaux

Figure 3.4 Fisher-Pry plot of the primary energy transition in the United States, 1850–2010. Data points calculated from statistics in Schurr and Netschert (1960) and EIA (2009). Shares of all fuels have seen some ups and downs but had changed little since 1960.



is highlighted by comparing the current shares with those that would be expected if the declining consumption of coal and oil were to mirror the ascent of these two fuels or if natural gas continued on its pre-1970 trajectory.

By 2010 coal would be down to only about 3% of the total primary energy supply, oil would be no higher than about 20%, while natural gas would have claimed about 75% of the market. And nuclear electricity generation has been yet another component of the U.S. primary energy source that has not conformed to the clock-like substitution model but that has obviously reflected the politics and economics of the U.S. nuclear development with its slow beginnings during the 1960s, major construction delays during the 1970s, the end of all new nuclear power plants orders in 1978, and impressive performance improvements during the 1980s and 1990s (Cantelon, Hewlett, & Williams, 1991; Smil, 2003). Construction of most of the stations ordered before 1979 was completed by 1990 (but the last reactor at Watts Bar station of the Tennessee Valley Authority, begun in 1973, was not completed until 1996!), subsequent generation gains came from improved performance of reactors, and the shares of nuclear electricity, much like those of fossil fuels, reached a plateau.

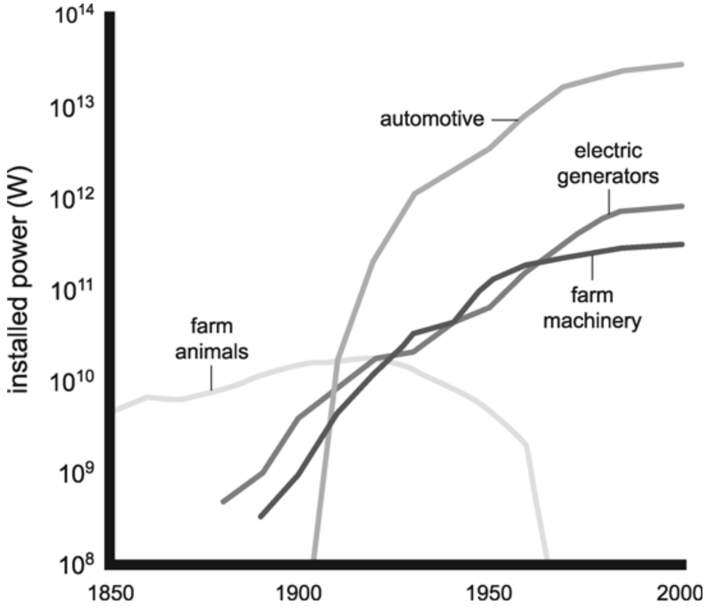
U.S. statistics also allow us to trace the transitions in the final uses of fossil fuels. In 1900 75% of all coal was burned simply to produce heat in industrial, institutional, and domestic settings, about 20% was used to power mobile steam engines, and less than 1% went to generate electricity; in 2000 nearly 90% of all coal was consumed in electricity generation and less than 10% to produce heat. Refined oil products have seen a similar decline in uses for heat and their rising prices have made them too valuable to be used in large-scale electricity generation: Their contribution peaked in 1978 when they generated nearly 17% of U.S. electricity and then it fell to less than 3% in 2000. Their high energy density made them the leading energizers of transportation: In 1900 that sector claimed less than 10% of the total supply and by 2000 it was about two thirds. Only the final uses of natural gas have not undergone any major transformation, with the production of heat claiming more than 90% in 1900 and about 80% a century later: Most of the rest is now going for electricity generation.

As already noted, the United States offers a unique opportunity for a fairly reliable quantification of the shifting shares of prime movers. Starting in 1850 the U.S. statistics list the total power of draft animals and of all inanimate prime movers disaggregated as automotive engines, electricity-generating equipment, machines in factories, mines, and on farms, engines on railroads, ships, and aircraft as well as sailing vessels and windmills. The two series of available statistics are not in a close agreement as far as the total power of working animals is concerned. Daugherty (1927) puts it at about 5.8 GW in 1849 and 16.8 GW in 1899, the U.S. Bureau of Census (1975) at 4.4 GW in 1850 and at about 14 GW in 1900, differences of, respectively, about 30% and 20%; I will use the more conservative series.

In 1850 draft animals accounted for about 70% of the country's total prime mover capacity; their share fell below 50% during the early 1870s as steam engines (mostly on railroads but also in factories and on ships) became the dominant prime mover. By 1900 the aggregate power of U.S. draft animals fell to just below 30% of the total and after 1910 its decline accelerated as internal combustion engines (mostly in passenger cars and trucks) became by far the largest aggregate repository of inanimate power, followed by steam turbines in electricity-generating plants. Aggregate power of draft animals claimed just 1% of the total by 1930 and less than 0.2% by 1950 (Figure 3.5). As for the total power of all prime movers (excluding human labor), it rose from about 6.3 GW in 1850 to nearly 48 GW in 1900, 355 GW in 1950, and 26 TW by 1990. Automotive engines have accounted for more than 90% of these totals since 1940, after rising from just 0.15% of the total in 1900 (when steam engines and draft animals were dominant) to 50% by 1917 and to 85% by 1930.

I have used this information on prime mover capacities to calculate a more relevant indicator of the prime mover transition, namely the shares of actually performed useful work, and I include human labor in this account. These calculations yield different shares than do the capacity numbers because the typical annual load factors of prime movers range from as little as 200 hours for car engines and about 1,000 (800–1,200) hours for draft animals to more than 6,000 hours for large steam turbogenerators. My estimates indicate that in 1850 nearly half of U.S. useful power was provided by animals, roughly a sixth by people, and just over a third by inanimate prime movers, overwhelmingly by steam engines complemented by water wheels, water turbines, and windmills.

Figure 3.5 Capacity of animate and inanimate prime movers in the United States, 1850–2000. Plotted from data in USBC (1975) and EIA (2009). Dominance of automotive engines is due to their very large numbers, now in excess of 250 million.



By 1900 human contribution declined to only 5%, animal work (despite a large increase in the total number of working horses and mules) fell below 20%, and steam engines and water turbines provided at least 75% of all useful power. By 1930 animate exertion supplied only some 3% of all useful power and internal combustion engines delivered more than a third of all useful inanimate power. By 1950 people and working animals contributed perhaps no more than 1% of all useful work and mass car ownership translated into more useful energy delivered by automotive internal combustion engines than by all other, mobile and stationary, prime movers.

But the situation was different on the country's farms. Total number of horses and mules on U.S. farms rose from about 5 million in 1850 to about 20 million by 1900 and it peaked in 1918 at 26.72 million, but by 1940 there were still more than 13 million draft animals (USBC, 1975). As a result, the combined power of inanimate prime movers in agriculture surpassed the aggregate power of draft animals only at the beginning of the 1920s; by 1930 machine power was about 60% of the total, a decade later 80%, by 1950 it reached 90%, and by 1960 there were still more than three million horses on U.S. farms but their aggregate power was only about 1% of the total. The transition from animate to inanimate prime movers was accomplished—its Fisher-Pry plot shows the expected fairly straight lines—and the USDA stopped counting the draft animals.

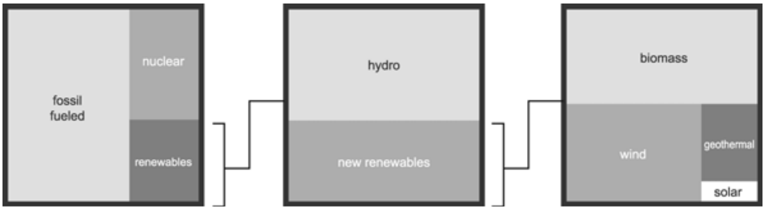
The last important case of U.S. energy transitions I will consider is actually a remarkable absence of such a process as far as the primary sources of electricity generation are concerned. As already explained, thermal and hydro generation began simultaneously in 1882 and by 1890 water power produced about 25% of the total output of approximately 1 GWh; 60 years later the total rose to nearly 400 GWh and water power (whose share rose to as much as 35% during the first two decades of the twentieth century) remained as important as in 1890, with 26% of the total. Its relative decline began only during the 1950s thanks to a rapid expansion of fossil-fueled generation, a process that continued during the 1960s (by 1970 coal-fired generation was 4.5 times the 1950 level, and the multiples for oil- and natural gas-fired generation were, respectively, about 5.5 and 8.3) when two new sources of electricity production—nuclear fission and geothermal steam—began to make small inroads.

Geothermal generation remained quite marginal (its share has never surpassed 0.5% of the total), but nuclear power, after passing the 1% mark in the first quarter of 1970, ended the decade with a nearly 11% share. Completion of many nuclear plants after long construction delays and better performance of established reactors pushed the share steadily upwards during the 1980s and the early 1990s and it touched the 20% mark in 1995 before stabilizing at just below that level. As a result, by the year 2000 fossil-fueled generation—largely coal-fired (73%), with natural gas at 22%, and liquid fuels at just 5%—was relatively more important (with about 72.5% of the total) than it was in 1900 when its share was about 65%.

While nuclear generation has become a major component of the country's electricity supply, the most remarkable fact concerning the U.S. electricity system has been a highly conservative nature of its development as the two pioneering modes of thermal and hydro generation that accounted for 100% in 1900 had retreated to only about 80% by 2000. This high degree of inertia is even more remarkable given the fact that those two modes of electricity generation had expanded about 650 times during the twentieth century, from less than 5 GWh to nearly 3 TWh. This, of course, means that any new generation technique will have to deliver many hundreds of GWh in order to become an important contributor to the overall supply.

The only recent entrant with that potential has been wind power, and its proponents stress its high rates of expansion driven by a combination of government subsidies, higher turbine capacities, and declining production costs. U.S. wind-driven electricity generation surpassed 0.1% of the total in 1999, 0.5% by 2006, and it reached 1.3% by the end of 2008. This has been undoubtedly a fast pace, but one that has not been unprecedented. U.S. wind generation rose 9.3 times between 2000 and 2008 (from 5.6 to 52 GWh), but during a similar early stage of its development nuclear generation increased much faster, more than 16-fold during the eight-year period between 1964 and 1972 (from 3.3 to 54.1 GWh). This is not surprising given the fact that average units in nuclear stations have power two orders of magnitude larger than average wind turbines.

Figure 3.6 U.S. generation of renewable electricity in 2008. Generation shares from EIA (2009). New renewables are still only at the very beginning of their coming ascent.



Continuation of the 2000–2008 rate of growth would have the U.S. wind turbines generating around 20% of all electricity by 2020 and roughly two thirds by 2030. As I will show in the next chapter, achieving the former share would require an extraordinary effort, while the latter share is impossibly high: No intermittent source could supply that much electricity in a nation with such a high per capita consumption, with such a relatively high base load, and with such poorly developed long-distance HV transmission. An even more sobering fact is that besides wind there is no other new generation technique that can be seen as a major near- to mid-term contributor at the multi-GW scale.

The two established but still only minor ways of renewable electricity generation—geothermal power with only 0.36% and combustion of biomass (wood wastes) with about 0.95% of the total U.S. generation—actually contributed relatively less in 2008 than they did in 1990, and solar conversions (PV and solar thermal generation) accounted for just 0.02% of America's electricity supply in 2008 (Figure 3.6). That was still two orders of magnitude below what might be seen as the beginning of a contribution that has a clear potential to make a substantial difference in coming decades. All in all, such terms as plateau, persistence, relative stability, and inertia—rather than rapid change and significant new departures—are thus the best descriptors of U.S. energy transitions during the past two generations.

JAPAN AND CHINA: THE ASIAN LEADERS

The Japanese case is noteworthy not only because of the country's unique history (about 250 years of pre-1853 isolation), the rapid rate of its modernization, and the size of its economy, but also because of its extraordinarily high dependence on imports: With the exception of South Korea (now with the world's thirteenth-largest GDP), no other major economy has so few domestic resources. Japan's energy transition followed the pattern that was experienced by a number of European countries as well as by the United States and Canada—but it did so at a distinctly accelerated rate. This compression was initially the function of Japan's late onset of modernization: When Commodore Perry's mission began the opening of Japan in 1853, the isolated country ruled by the xenophobic Tokugawa shogunate was still a very traditional society whose energy basis rested on human labor and on combustion of wood and large-scale charcoal production in the country's mountainous regions (where household heating was required during snowy winters) and on the burning of rice straw and other crop residues in the lowlands.

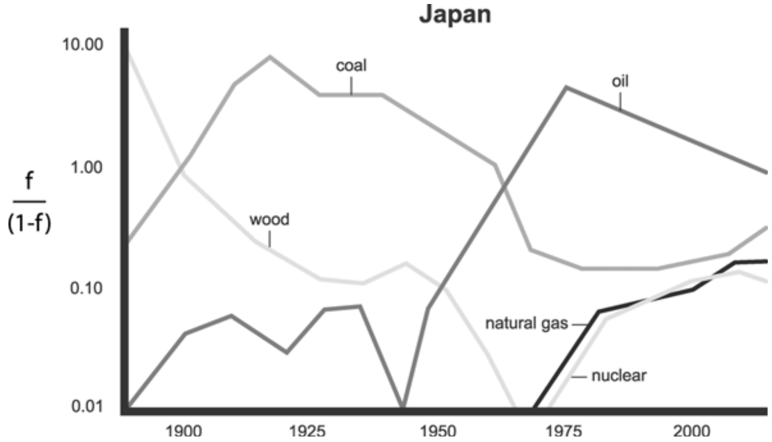
After the Meiji Restoration (resumption of imperial power and the transfer of the capital from Kyoto to Tokyo in 1867) the country pursued a broad-based program of modernization, and energy transition became one of its critical components. Progress of Japan's industrialization and militarization was so rapid that in 1895 Japan defeated China in a brief war and 10 years later it was once again victorious in a longer conflict with the imperial Russia (Jansen, 2000). Japan's historical statistics contain a complete energy balance series starting in 1880—when wood and charcoal supplied 85% of all primary energy, coal 14%, and oil just over 1%—and hence they allow us to quantify the country's energy transition from its early stages (JSA, 1987–1988; Bank of Japan, 1999; IEE, 2009).

Coal consumption surpassed the biomass energy in 1901 (when it claimed 57% of the total vs. about 39% for wood and charcoal) and rapid pre–WWII industrialization increased the aggregate energy use about 2.6-fold between 1920 and 1940, with the biomass share falling to only about 10%, coal (after peaking at about 77% in 1917) to about 66%, and hydroelectricity rising to 16% of the total. Defeat in World War II cost the country dearly: In 1946 energy use was 55% below the 1940 peak and that level was not surpassed until 1955. By that time Japan's swiftly rising oil imports were shifting the country's primary energy use toward hydrocarbons: Oil use surpassed coal energy in 1961 (with nearly 41% vs. about 39%; it was also the year when the domestic coal production peaked at about 55 Mt of coal equivalent by 1970 it reached almost 72%, and three years later it topped 77% of the total energy supply, a relative peak that was virtually identical to that reached by coal in 1917.

In 1974 (following OPEC's first sudden oil price rise) oil imports declined for the first time since 1946 and deeper reductions followed after 1977: In 1982 Japan imported 25% less oil than in 1973. After a short period of stagnation oil import growth resumed in 1987 but further decline came after 1990 with the demise of Japan's bubble economy and by the century's end the oil import was almost exactly the same as in 1980, and by 2008 it was nearly 15% lower. Oil's falling share of primary energy consumption (from 66% in 1980 to 49% by 2000 and 44% in 2008) has been accompanied by steadily rising shares of imported LNG (from 6% in 1980 to 14% in 2000 and nearly 17% in 2008) and nuclear electricity generation (from less than 5% in 1980 to 11% in 2008) and by a notable post-2000 rise of imported steam and metallurgical coal, whose share remained fairly stable between 1980 and 2000 (17% and 18%, respectively) but surpassed 25% by 2008.

Once again, Fisher-Pry plots of Japan's post–WWII transition do not confirm any inevitably scheduled trends (Figure 3.7). Even during the pre-1973 period

Figure 3.7 Fisher-Pry plot of the primary energy transition in Japan, 1880–2010. Data points calculated from statistics in JSA (1987–1988) and IEE (2009). A highly idiosyncratic transition pattern, with only natural gas and coal being recently ascendant.



when oil exports were surging coal's share was not correspondingly plummeting, and it has not only stabilized since 1980 but has even grown. Similarly, the oil share has been retreating at a relatively slow pace after reaching its peak in 1973. Growth rate of LNG imports was almost matching the rise in oil imports during the 1970s but it slowed down considerably during the 1980s and even more so since the early 1990s. And there is nothing on the energy horizon to displace these three fossil fuels: Since 1945 water power's share has fallen steadily, from nearly 40% in 1946 (an anomalously high share created by the war destruction of other components of Japan's energy supply) to about 15% by 1960, 3.4% by 2000, and 3% in 2008, and nuclear generation—after a strong start during the 1970s and the 1980s when it rose from just 0.3% to almost 10% of the total—peaked in 1999 at nearly 13% and has since declined to about 11% of all primary energy by 2008.

Another notable characteristic of Japan's energy transition has been the country's rising dependence on imported fuels. At the beginning of the twentieth century Japan's energy imports were less than 4% of the total supply and by 1940 crude oil and refined products still accounted for no more than 7% of the total. After the post-war low of just over 2%, the 1940 share was reached again by 1950/1951, by 1960 imports surpassed 50% of the total supply, and since 1970 they have been above 99%. As these imports grew their composition and their magnitude have changed substantially: In 1970 Japan imported about 26% of its natural gas, 57% of its coal, and 100% of its oil consumption; by 2008 all of these shares were virtually 100%, and total imports had nearly doubled from about 10 EJ in 1970 to more than 18 EJ by 2008. Given this near total dependence on fuel imports Japan faces a particularly daunting task of replacing imported fossil fuels by renewable energies harnessed within its territory.

China has the earliest documented use of coal (in iron smelting), going back to the end of the Han dynasty. Coal was packed around tube-like crucibles filled with iron ore and the liquid iron was cast into interchangeable molds to produce plowshares, thin-walled cooking pots, and pans Although locally important, coal was not widely used, and even after modern coal production began during the 1880s its growth was slow and for decades it continued to be dwarfed by the country's demand for biomass energies. Given China's large rural population this demand was always huge in absolute terms—while per capita biomass energy consumption was always only a fraction of Western European and U.S. rates—because many regions have been deforested for centuries, and because recurrent droughts and poor harvests limited the availability of crop residues in the lowlands.

These rural energy shortages were widespread even at the beginning of China's current modernization drive. The first series of rural energy surveys done across China in 1979 set the average daily requirements at just 3.25–3.75 MJ of useful energy per day per capita (Smil, 1988). Given the average combustion efficiency of about 10%, this works out to annual per capita combustion of less than 13 GJ of biomass fuels, or only about 800 kg of woody biomass or nearly 900 kg of crop residues. In contrast (as shown previously in this chapter), annual preindustrial fuelwood use in the forest-rich United States averaged nearly 90 GJ/capita.

But the 1979 surveys showed that even the minimum energy needs were not often met, with the average supply shortfall amounting to just over 20%. In 1980 it was estimated that 500 million peasants (63% of the total) suffered from serious fuel shortages for at least three to five months of the year and by 1982 the nationwide share was still nearly 50%, with the highest rates, in excess of 60%, in the worst affected provinces of Xinjiang, Hebei, Hunan, and Sichuan and in the most densely inhabited parts of Tibet. By the late 1980s rural energy shortages were much reduced thanks to the rising output of coal from small local mines, return of privately owned wood groves, and improved stove designs (raising typical efficiencies from just 10–15% to 25–35%).

My approximate reconstruction of China's primary energy use shows the share of biomass energies fairly constant during the first half of the twentieth century, falling only marginally from more than 99% in 1900 to nearly 98% by 1949. Subsequent rapid increases in coal output lowered it to about 60% by 1957 and to 50% of the nationwide energy use by the mid-1960s. But in the countryside crop residues and woody phytomass still supplied about 90% of all household energy use during the early 1970s and this share fell to below 70% by 1980, below 50% by 1988, and to 33% by 1998 (Zheng, 1998; Fridley et al., 2008). In terms of the total primary energy supply the biomass supplied about 40% of the total in 1970 and in 1979 crop residues, firewood, and dung cakes still accounted for no less than 28%. By 2000 this share was more than halved to 13% and by 2007 it fell below 10%.

China's tumultuous modern history—collapse of the last imperial dynasty (1911), subsequent loss of any central government control, war with Japan

(1933–1945) and the protracted civil war between the Nationalists and the Communists (1927–1936, 1945–1950)—had played a role in prolonging the country's transition from biomass to fossil fuels and hydroelectricity: It took about 65 years for these modern energies to progress from 1% to 50% of the total primary energy supply (1900–1965). Only then the pace of substitution speeded up as the biomass energy share was reduced to 25% in less than 20 years (1965–1983), but the reduction from 25% to 10% took more than two decades (1983–2006). In absolute terms this means that in 2006 China's biomass energy was 25% above the 1980 level and the highest ever in China's long history, amounting to nearly 200 Mtoe, or more than the total annual 2008 primary energy supply in Mexico or Italy.

Much as in Europe or the United States, China's post-1949 transition from biomass to fossil fuels was dominated by coal and details can be easily reconstructed from available statistics (SSB, 2009; Fridley et al., 2008). China's case is an excellent illustration of both the slowness of energy transitions and of the imperatives of scale: The country's demand for energy has been so large and its huge coal resources could be tapped so readily that it has proved impossible to displace to any significant extent the fuel that is not only inconvenient to handle and gives rise to major air pollution problems but whose extraction (as practiced in China, particularly in small rural mines) has been also uncommonly deadly: During the first five years of this century coal-mining fatalities averaged about 6,200/year, or nearly four deaths for every million tonnes of coal (Fridley et al., 2008).

Total coal output in mines opened largely with foreign investment surpassed 1 Mt only by 1903, in 1911 it was just over 5 Mt, during the early 1930s (before Japan's invasion of Manchuria in 1933) it was approaching 30 Mt, and in 1940 it reached about 46 Mt. When the Communist Party won the protracted civil war and took control in 1949 coal output was only about 32 Mt (Thomson, 2003). China's first Stalinist Five-Year Plan boosted the extraction to 130 Mt by 1957 and a key goal of Mao's infamous Great Leap Forward was to produce more coal and steel than the United Kingdom. Official (grossly exaggerated) statistics had the coal extraction reaching nearly 400 Mt by 1960. Whatever the real total, most of this fuel was of inferior quality (with at least two-fifths of it produced by primitive local mines) and it was largely wasted in the Maoist campaign of iron smelting in primitive "backyard" furnaces which, in turn, was a principal reason for the world's largest man-made famine as it diverted labor from food production (Smil, 1999).

After precipitating the three famine years the Leap collapsed and coal production returned to more orderly ways, with output rising to about 350 Mt by 1970 and surpassing 600 Mt by 1978 when Deng Xiaoping took control of the Party and set China on the road toward post-Maoist modernization. China's post-1980 record of economic growth, export performance, adequate food production, and rising standards of living would have been impossible without abandoning the key Maoist precepts—and without continuous dependence on coal. So much has changed in China since 1980, but high reliance on coal has remained a fundamental constant.

In the early 1950s China derived more than 95% of its primary commercial energy (leaving biomass contributions aside) from coal, and the share was still over 90% by the end of the first Five-Year Plan in 1957. After a supergiant Daqing oil field went into production coal's share decreased to about 86% in 1965, 80% in 1970, and 72% by 1975. During the first year of the modernization drive the share actually rose to 76%; by 1985, a decade later, it declined only marginally to just over 74%; by 2002 it was down to just over 65% but then it began rising once again and it just surpassed 70% in 2008. Given an extraordinary rise of China's total primary energy supply (it doubled between 2000 and 2008), this means that China's coal extraction more than doubled in just eight years, from about 1.3 Gt in 2000 to nearly 2.8 Gt in 2008.

With China's coal shares at nearly 73% in 1980 and at 70% in 2008 it is obvious that during the three decades of rapid modernization there was only the tardiest of transitions from solid fuel to hydrocarbons. China's extraordinary dependence on coal means that the country now accounts for more than 40% of the world extraction, and that the mass it produces annually is larger than the aggregate output of the United States, India, Australia, Russia, Indonesia, and Germany, the world's second- to seventh-largest coal producers. No other major economy, in fact no other country, is as dependent on coal as China: The fuel has also recently accounted for 95% of all fossil fuels used to produce electricity and as the thermal generation supplies nearly 80% of China's total generation it is the source of more than 70% of electric power.

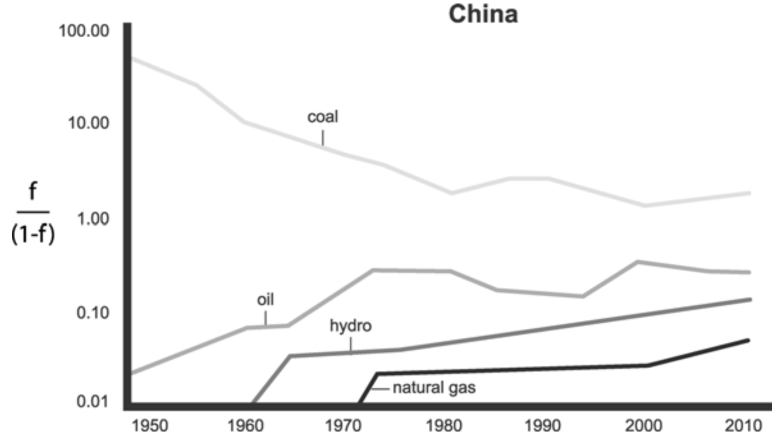
China was self-sufficient in crude oil between the mid-1960s (when it produced less than 15 Mt/year) and 1992 when it extracted about 142 Mt, exported 39 Mt of crude oil and refined products, and imported about 28 Mt. Imports remained low, below 50 Mt/year, until 2000; by 2004 they surpassed 100 Mt and by 2008 they were nearly 180 Mt, making China the world's third-largest buyer of oil (after the United States and Japan). In addition, between 2000 and 2008 China's domestic crude oil extraction rose by 17% to about 190 Mt/year—but even this combination of steadily growing production and rapidly rising inputs could not prevent the oil's share of primary energy supply from falling from the peak of nearly 24% in 2002 to less than 19% by 2008.

As explained in the second chapter, China was also the world's earliest user of natural gas, but the country's gas resources have turned out to be surprisingly limited, particularly when compared to other countries with large territories and with extensive hydrocarbon-yielding sedimentary basins. In 2008 the ratio of gas/oil reserves (expressed in energy equivalents) was 3.3 in Russia and 1.5 in the United States but less than 1.0 in China. As a result, domestic natural gas production has been only a marginal contributor to the country's primary energy supply: It rose above 1% of the total only in 1971 and it has yet to reach 5% (in 2008 it was 3.6%). The share will rise appreciably only after most of the recent large LNG projects (with the gas from Australia, Indonesia, and Qatar) will have reached their planned capacity.

In contrast to its relatively poor natural gas production potential, China has the world's largest water power capacity and its development brought its share of the total primary energy supply from less than 2% during the early 1950s to 5% by the late 1980s, and the subsequent development of large hydro projects (including Sanxia, the world's largest hydro station on the Chang Jiang in Hubei, whose installed capacity will be eventually 22.5 GW) increased the share to nearly 7% by 2008. Hydroelectricity thus remains much more important than nuclear generation: Many bold plans for its development remained just that and its share has yet to reach 1% of the total (it was 0.8% in 2008). Unlike in all major Western economies and Japan where the two kinds of hydrocarbons now account for the largest share of primary energy supply, China has thus basically accomplished only the transition from biomass to coal, and there is no early prospect (no prospect at all?) for hydrocarbons surpassing coal's contribution.

In 2008 China's combined consumption of crude oil and natural gas covered just over 20%, hydroelectricity is unlikely to ever reach 10% of the total, and nuclear electricity remains a marginal contribution. Although in absolute terms all fuels, including biomass, are at record-high levels, with per capita consumption rates unprecedented in China's long history, in relative terms China is now much more dependent on coal (with all environmental, safety, and logistics implications such a dependence implies) than it was at the outset of Deng Xiaoping's reforms in 1979: At that time coal supplied 52% of all primary energy supply (including all biomass), while in 2008 coal's share reached 64% of the total (Figure 3.8).

Figure 3.8 Fisher-Pry plot of the primary energy transition in China, 1950–2010. Data points calculated from statistics in Smil (1976), Fridley et al. (2008), and SSB (2009). Another highly idiosyncratic pattern of a national energy transition marked, once again, by a notable post-1970 stagnation of coal and oil shares.



China thus presents an even stronger case of arrested energy transition than does the United States, where coal's share has remained fairly stable since the early 1980s: In China's case coal's share has actually risen by nearly 25% during the same period!

NEW ENERGY SUPERPOWERS: RUSSIA AND SAUDI ARABIA

The common denominator here is, of course, the superpower status of the two countries as far as their crude oil and natural gas reserves and production are concerned. Russia has nearly a quarter of the world's natural gas reserves, is the fuel's largest producer, and it is also the second-largest producer of crude oil. Saudi Arabia has more than a fifth of the world's crude oil reserves, it has been the fuel's leading producer since 1992 (when it surpassed Russia), and its natural gas reserves rank fifth worldwide (after Russia, Iran, Qatar, and Turkmenistan). But there are two other notable similarities, namely the relatively late shift toward fossil fuels and a fairly recent attainment of higher levels of domestic energy consumption. These conclusions may be surprising to all those who had lived through the decades of the Cold War when the USSR was seen as a very formidable adversary deserving the superpower label.

But the pre-revolutionary Russia was far behind the United States in terms of energy consumption, and the country's tipping point from wood to fossil fuels and primary electricity came only during the Soviet era (about half a century after coal surpassed wood in the United States), and the overall Soviet per capita energy consumption, and even more so the discretionary energy use by households, have never approached the U.S. levels. On the other hand, given Russia's rich resource endowment and its pioneering role in the development of oil industry, it is hardly surprising that the early phases of the Russian primary energy transitions had some key features common with the U.S. pattern.

History of the Russian Empire (pre-1917), of the USSR (beginning in 1917 with the Bolshevik take-over, or in 1921 with the formal constitution of the Soviet Union), and the new Russia (following the peaceful dissolution of the USSR in December 1991) presents numerous challenges of adjusting statistics due to changing territorial extent and population counts. However, all but a small portion of the transition from wood to fossil fuels had taken place during the decades of the Soviet power (1917–1991), the era for which basic fuel and annual electricity statistics are available from the USSR's Central Statistical Office (*Tsentral'noie statisticheskoie upravlenie SSSR*), although their accuracy has been always questionable.

The Russian Empire, whose long history ended with the Communist *coup d'état* in November 1917, was an epitome of wooden society. Although its Caspian (Baku) oil deposits were the site of some of the world's first drilling and refining efforts (even predating the U.S. activities; see Figure 2.3) and although commercial coal mining began during the early 1830s, its aggregate extraction of fossil fuels remained limited and it amounted to a tiny fraction of the U.S. output. In 1850, when the United States mined more than 7.5 Mt of coal, Russia produced only about 50,000 t, roughly a 500-fold difference in per capita terms. And even in 1913 the U.S. per capita output of fossil fuels was 20 times the Russian per capita extraction of coal and crude oil. During that last peaceful year before the upheavals of World War I, the Communist take-over, and years of civil war, Russia produced nearly 30 Mt of coal, 10 Mt of oil, and less than 2 Mt of peat, an equivalent of about 1.4 EJ of primary energy (or 8.8 GJ/capita) compared to the U.S. extraction of fossil fuels that added up to 17.6 EJ or 181 GJ/capita.

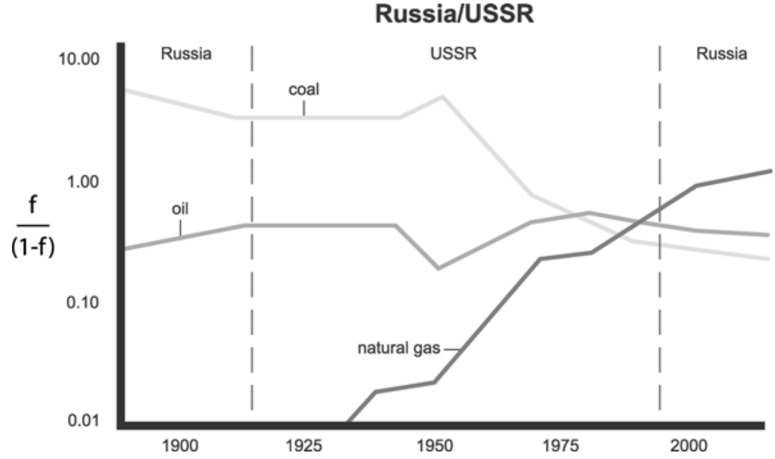
Soviet historical statistics put the share of fuelwood in 1913 at 20% of primary energy production (TsSU 1977) but that obviously refers only to commercially produced fuel whose total prorated to merely 1.5 GJ/year per capita, roughly 1/20 of the U.S. per capita rate in 1900, half of the Russian rate for 2005. Such a low rate was only a very small fraction of energy needed to heat a typical Russian wooden residence. Even a small house in northern part of European Russia or in Siberia would have required at least 100 GJ/year and recall that in 1850 the U.S. households averaged no less than 100 GJ/year. My best estimates indicate that by 1913 wood supplied no less than 75% of Russia's primary energy and that the aggregate consumption of fossil fuels and primary electricity surpassed that of fuelwood only during the early 1930s (compared to the U.S. tipping point half a century earlier in 1884/1885).

Russia's oil production surpassed the coal extraction already by 1890 and in 1899 the country became briefly the world's largest producer of crude oil (just over 9 Mt/year) with most of it exported by foreign investors who dominated its extraction (Samedov, 1988). Because of these relatively large exports, domestic consumption remained low: In 1900 it was only about 10% higher in energy terms than the total coal combustion. Baku production began to decline after 1900 and by 1913 it was two thirds of its 1901 peak and Russia's coal consumption was more than twice as large as its oil use. By 1950 this difference was roughly 4.5-fold and coal remained the largest contributor to the Soviet primary energy supply until 1974 (or nearly three decades longer than in the United States) when it was finally surpassed by crude oil (Figure 3.9).

By the time of the USSR's dissolution in 1991 coal contributed just over 20% of the Soviet energy use. The post-Communist era has been marked first by repeated strikes, chaotic coal industry privatization, and closures of old inefficient mines and then by frequent changes of ownership and mergers within an unstable industry. This combination of events has had a largely negative impact on the level of Russian coal production (Ignatov & Company, 2009). While the country's coal reserves (particularly in Siberia's Kansk-Achinsk basin) remain enormous, coal's share in primary energy supply has been declining since 1991 and by 2008 it accounted for less than 15% of the total (Figure 3.9).

Coincidentally, 1974, the year when oil use surpassed coal consumption, was also the year when the Soviet crude oil extraction surpassed the U.S. total and

Figure 3.9 Fisher-Pry plot of the primary energy transition in the Russian Empire, the USSR, and the Russian Federation, 1900–2010. Data points calculated from statistics in TsSU SSSR (1977) and BP (2009). Wood was the largest source of primary energy until the late 1920s, but as there are no reliable statistics of its use, and as hydro and nuclear generation supply each only about 5% of the total, the plot shows only fossil fuels.



the USSR became the world's largest oil producer, the position it occupied until 1991. This distinction was achieved thanks to two successive spatial transitions experienced by the Soviet oil industry. Baku produced 75% of Russia's oil in 1913 and still nearly 72% of all Soviet oil in 1940 but by 1960 its share was down to about 12%. The "second Baku"—the Volga-Ural region where oil production began in 1929 and where the first giant oilfield (Tuymazy) was discovered in 1937 and the second one (Romashkino) in 1948—became dominant during the 1950s and it produced 70% of the Soviet oil by 1960.

The second shift began with the discoveries of supergiant fields in Western Siberia, an oil-bearing province twice the size of Alaska. The first indication of that basin's hydrocarbon riches came with an accidental gas and water gusher right at the outset of drilling R-1 Beryozovo well in September 1953 (Karpov, 2008). Principal discoveries came only during the early 1960s with the discoveries of supergiant Samotlor and Ust'-Balyk in 1961 and Mamontovo in 1965 (EIA, 1997). These fields were rapidly developed and connected by long-distance pipelines to the European USSR and to Central and Western Europe, and their output still dominates the Russian extraction.

As a result the Soviet oil production nearly quadrupled during the 1950s and then it more than doubled (growing roughly 2.4 times) during the 1960s so that even with rising exports oil's share of domestic primary energy consumption rose from 16% in 1950 to 26% in 1960 and 34% in 1970. Oil's contribution peaked between 1974 and 1983 when it reached a brief plateau of between 35% and 37%

and natural gas became the country's leading primary fuel in 1984 (Figure 3.9). Discoveries of the world's largest gas fields in Western Siberia—Urengoy in 1966, Yamburg and Yubileinoye in 1969 (EIA, 1997)—made the USSR, and Russia, the world's largest repository of gaseous fuels: In 2008 Russia's gas reserves accounted for nearly a quarter of the world total, a higher relative share than the Saudi share of global oil reserves. Their rapid development more than quadrupled the Soviet gas output during the 1960s, more than doubled it during the 1970s, and nearly doubled it during the 1980s (Kortunov, 1967; CIA, 1978; Smith & Thomas, 1982).

The USSR became the world's largest natural gas producer by surpassing the United States in 1983, and for the rest of its existence it also remained by far the world's largest gas exporter as most of the European countries have gradually become critically dependent on the pipeline deliveries from Western Siberia. Even with these large export commitments the USSR was able to boost its share of gas consumption from just below 10% of the total in 1960 to just over 20% a decade later and then to 32% in 1980 and 41% in 1990—and the fuel became even more prominent in post-1991 Russia, where its share rose to nearly 53% by the year 2000 and to 55% by 2008 (Figure 3.9).

History of the USSR was shaped by deliberately grandiose electrification plans. Lenin's famous dictum that Communism equals Soviet power plus electricity was put into practice by the establishment of the State Commission for Electrification of Russia (GOELRO) and its plans for expansion of both thermal and hydro generating capacities (Nesteruk, 1963). These were not always the most efficient ways to develop the country's electric industry, and projects completed during the pre–WWII years also exacted a high price in terms of human suffering and death (many were built with forced labor from GULag). Even more grandiose plans followed after World War II but, fortunately, only some of them were realized: Perhaps the greatest unrealized project was, thankfully, the diversion of great Siberian rivers to the arid core of the Soviet Central Asia.

Soviet achievements have been particularly notable in developing the country's hydro generation potential, with about 100 GW of economically exploitable power, the second highest (far behind China and just ahead of Brazil) in the world (Nesteruk, 1963; WEC, 2007). Pre–WWII hydro capacities rose from just 16 MW in 1913 to nearly 1.6 GW by 1940 and the postwar growth brought them to about 15 GW by 1960, 52 GW by 1980, and 85 GW by 1990. The USSR also built several of the world's largest hydro projects on the Angara (Bratsk with 4.5 GW completed in 1967) and the Yenisei (Krasnoyarsk, 6 GW, operating since 1964), and the world's highest dam (300-m Nurek on the Vakhsh river in Tajikistan with 3-GW capacity).

But given the country's large fossil fuels consumption even such a vigorous development of hydroelectricity has not been able to make a significant difference: Water power's share rose from just 0.5% of all primary energy in 1950 to 3.8% by 1970 and then it remained at that plateau until 1991. And despite some early bold plans for its development, the USSR's nuclear electricity generation—made infamous by the catastrophic accident of the Chernobyl reactor in the Ukraine in 1985 (Bariakhtar, 1995)—never became as important as the hydroelectric generation: In 1990 it supplied 3.4% of all primary energy. In the post-Communist Russia its share has been somewhat higher, but at 5.4% in 2008 it was still marginally lower than hydroelectricity's contribution (5.5%). However, by 2008 a newly independent Ukraine derived about 15% of all primary energy from its nuclear stations (including the undamaged units at Chernobyl), a share higher than in Germany.

The history of Soviet energy consumption is one of impressive absolute gains, be they in aggregate or per capita terms, as total domestic energy supply increased from 1.1 EJ in 1913 to 59 EJ in 1990 (a nearly 54-fold expansion) and as annual per capita use had tripled from about 70 GJ to more than 210 GJ. But the country's energy transition—disrupted by the two devastating wars and a protracted civil war following the Communist seizure of power, and affected by decades of Stalinist mismanagement—has been very idiosyncratic, with its long dominance by coal, decades of relatively high share claimed by oil that amount to an extended plateau (30% in 1913, 27% in 1940, 34% in 1970, 30% in 1990), and a rapid post-1950 rise of natural gas.

Saudi Arabia's economic development is a perfect example of a very rapid transition from a poor preindustrial and largely nomadic society, to one of the world's largest energy consumers and the largest crude oil exporter—all of that due to the combination of unrivaled oil resources and a relatively small, albeit rapidly growing, population (about 26 million in 2010, compared to Iran's 75 million, Nigeria's nearly 160 million, and Indonesia's more than 230 million). When the country was created in 1932 as a loose federation of desert tribes with Abdul Aziz as its king its primary energy consumption was at a very low subsistence level (less than 5 GJ/capita, comparable to today's use in the poorest regions of sub-Saharan Africa), with most of the fuel for cooking and water heating coming from the burning of biomass (including desert brush twigs, camel dung, and date kernels) by the desert nomads and by using imported coal and kerosene in a few coastal settlements.

The king granted the oil concession to Casoc (California Arabian Standard Oil Company) in 1933, first oil discovery came in 1938, and the first small tanker shipment came a year later (Clark & Tahlawi, 2006). In 1944 Casoc changed its name to Aramco (Arabian American Oil Company) and a year later, when the refinery in Rās Tanūra (now the world's largest oil-loading terminal) began its operation, the country produced more than 5 Mt of oil and the output reached nearly 27 Mt by 1950. By the mid-1950s it became clear that the country has both the world's largest supergiant field, al-Ghawār, and the world's largest offshore oil field (Safaniya). Oil output more than doubled during the 1950s and then it nearly tripled during the 1960s. Saudi oil production continued to increase during the 1970s (with only a single-year decline in 1975) and it reached its highest level in 1980 with 495.89 Mt.

This was followed by a precipitous slump (caused by OPEC's record-high demand-destroying price run-up between 1979 and 1981) to just 172 Mt by the year 1985, but after the demise of the USSR the country became the world's largest oil producer by surpassing the Russian extraction in 1992, and it has continued to maintain this primacy ever since. In contrast to rapidly rising exports, the Saudi domestic consumption remained rather low until the mid-1970s (in 1975 it was virtually unchanged from the 1965 level), but then it tripled by 1985 and nearly tripled again by 2008, reaching about 175 Mtoe or roughly 270 GJ/capita (compared to about 175 GJ/capita for the richest EU countries). This means that by the late 1970s Saudi per capita use of primary energy surpassed the means of the richest European states and that the country's transition from preindustrial subsistence to a high-energy society took just 40 years when measured from the first oil discovery in 1938 or (when using a more meaningful delimitation) only about 25 years when measured from the beginning of the post–WWII modernization during the early 1950s.

But two important caveats are in order. The high mean of the Saudi per capita energy consumption is misleading because a large part of the overall energy demand is claimed by the oil and gas industry itself and because it also includes substantial amounts of bunker fuel for oil tankers exporting the Saudi oil and refined products. Average energy use by households remains considerably lower than in the richest EU countries. Even more importantly, Saudi Arabia's high energy consumption has not yet translated into a commensurately high quality of life: Infant mortality remains relatively high and the status of women is notoriously low. As a result, the country has one of the world's largest differences in the ranking between per capita GDP and the Human Development Index (UNDP, 2009). In this it is a typical Muslim society: In recent years 20 out of 24 Muslim countries in North Africa and the Middle East ranked higher in their GDP per capita than in their HDI—and in 2007/2008 the index difference for Saudi Arabia was –19 while for Kuwait and Bahrain it was –8 and for Iran it was –23.

The Soviet and Saudi examples illustrate the rapidity with which even a large economy or a latecomer to modern development can accomplish its energy transition—but it must be remembered that this would not have been possible without those countries' exceptionally rich fossil fuel (and in the Russian case also of water power) endowment. Consequently, the Soviet or Saudi energy transitions have limited implications for economies that have minimal, or no, domestic resources and (to make the bridge to the next chapter) they offer no insight into the coming shift from fossil fuels to renewable energies. Moving away from fossil fuels will be a protracted affair even in those countries where the requisite resources are readily available, because every society will have to deal with the twin challenge of low power density and intermittent flows of renewable energies.

Chapter 4

COMING TRANSITIONS: EXPECTATIONS AND REALITIES

The history of energy transitions—long, complex, and not easily amenable to simple judgments, sweeping generalizations, and crisp deductions—can be used to support a range of conclusions. Moreover, as is always the case with long-term perspectives, even the most robust and conservatively stated conclusions based on careful examination of this evidence may not have a great deal of relevance for outlining the most likely pace and extent of any future developments. This may be because of an extraordinary difficulty and exceptional nature of the coming energy transition—but, given the enormous challenges of ushering in a post-fossil world, it may also be because of the possibility of an unprecedented and persistent commitment to a rapid change.

Regrettably, my interpretation of the past evidence and my understanding of the current capabilities to act, and to persist, favors the first reason: Lessons of the past energy transitions may not be particularly useful for appraising and handicapping the coming transition because it will be exceedingly difficult to restructure the modern high-energy industrial and postindustrial civilization on the basis of non-fossil—that is, overwhelmingly renewable—fuels and flows. I use the qualifier "overwhelmingly" in order to leave some room for a possibility of substantially increased nuclear electricity generation—although the combined challenges of the industry's public acceptance, long-term fuel availability, permanent waste storage, and nuclear weapons proliferation do not make any early vigorous and widespread renaissance very likely.

At the same time, any unbiased *sine ira et studio* approach must recognize that affluent countries could make the coming transition considerably easier by substantially reducing their clearly excessively high per capita energy use and by making the shift to new energy foundations one of its key concerns to be pursued with persistence and determination. As yet, there is very little evidence of any determination to embark on such a challenging, costly long-term commitment but this does not mean that the future course of energy use is inescapably predetermined and that we are inexorably entering a dangerous energy *cul-de-sac*. Nothing concentrates minds as much as acute crises do, and so it is possible that a future deep and protracted disruption of existing production/consumption arrangements will help to accelerate the coming energy transition.

Our energy choices have not been foreclosed—but we have to recognize that they are, at least in the near- to mid-term, restricted by availability and convertibility of individual resources and by the pace of technical innovation and social adaptation. Following my long-standing practice of not making any quantitative point forecasts I will not offer any absolute predictions for particular years or time periods, be it on the global scale or for individual nations. Instead, I will examine first the fundamental contours of the coming energy transition by explaining the magnitudes of available non-fossil resources and major constraints on their conversions, above all their low power densities.

British, French, and U.S. histories of energy use show that all early modernizers had experienced a slow (even very slow) transition from biomass fuels to coal. This is not surprising, because that epochal shift took place during the earliest stages of Western industrialization: Indeed, it had largely defined it. During that time gaps between invention, innovation, and large-scale commercial diffusion were often so long because of the limited abilities to perfect newly invented production methods and prime movers and because of the restricted or disrupted capacities for their widespread adoption. Several reasons for those slow advances stand out: Scientific understanding of the underlying processes was often inadequate, suitable high-performance materials needed for mass production (steel in particular) were either unavailable or in short supply, manufacturing processes were inadequate as far as both qualities and capacities were concerned, requisite infrastructures took a long time to complete, and large-scale competitive markets were absent.

In contrast, it appears that today's situation is markedly different, a state of affairs that should make the coming transition to non-fossil energies a less taxing experience. After all, we have now an enormous wealth of relevant scientific understanding, as yet no disruptive shortages of high-performance metals and materials that are needed at every stage of energy harnessing and conversion are imminent, advanced manufacturing processes are able to prototype new designs rapidly and to take advantage of the economies of scale (recent scaling-up of wind turbines to multi-MW ratings is an excellent example of these capabilities), our technical capacities to put in place new infrastructures are unprecedented, and there are highly competitive global markets for nearly all important techniques and products.

As a result, there has been a growing perception that—given the abundant renewable energy resources and steadily improving technical capabilities to harness those flows—all that is needed to bring about a relatively rapid shift away from fossil fuels is a determined effort that, at least in its opening stages, should be guided and supported by far-sighted government interventions, and many governments have expressed these expectations in terms of binding targets to be supplied by renewable flows at specified future dates. I will address the future rate of these developments in two ways, first by putting the expected pace of the coming transitions into a wider context by looking at some inexplicably neglected but universally valid aspects of technical innovation, including infrastructural demands and a remarkable inertia of prime movers, and then by describing some notable cases of past and present national aspirations of shifting toward renewable energies. I will not offer any grand, overarching conclusions: Instead, I will end with some qualified observations and with summaries worded as cautious anticipations.

RENEWABLE ENERGIES: RESOURCES, CONVERSIONS, AND CONSTRAINTS

Two reasons for moving toward non-fossil futures stand out at the beginning of the twenty-first century: concerns about long-term effects of global climate change, and worries about rapidly approaching depletion of low-price, high-quality fossil fuels. The first concern stems from a widely accepted understanding that, as complex as climate change may be, anthropogenic emissions of fossil carbon have emerged as its most pronounced and certainly the most readily identifiable driver (IPCC, 2007; see Figure 1.3). Continuing reliance on fossil fuels could be possible if it were accompanied by mass-scale underground or undersea sequestration of carbon or by (an even less technically mature option) planet-wide geoengineering interventions (such as shading the Earth, boosting the planet's albedo, increasing the atmospheric aerosol loading). But certainly the surest way to prevent excessive global warming and to keep the average global temperature increase within acceptable limits (most likely no more than 2°C above the preindustrial mean) is to reduce the reliance on fossil fuels by gradually shifting the world's energy supply to a renewable basis and eventually eliminating coals and hydrocarbons.

The second concern is related above all to the alleged imminence of global peak oil extraction to be followed by a fairly rapid decline of global oil production, but there have been also some indications that the world's coal resources may be significantly less abundant than the widespread impressions would indicate (Rutledge, 2008).

This is not a place to assess the merits of these concerns; many recent works have done so in a great detail. But even if the current perceptions of these threats turned out to be exaggerated, there are many other good reasons for favoring a shift of the global energy supply away from fossil fuels, whose extraction and conversion has many undesirable environmental impacts including the emissions of CH_4 (a more powerful greenhouse gas than CO_2), black carbon (another important factor in atmospheric change), and oxides of sulfur and nitrogen (both being the precursors of acid deposition and the latter one also a key ingredient in the formation of photochemical smog).

An entirely different set of concerns favoring transition to a non-fossil world stems from financial and strategic considerations arising from unpredictably rising (and fluctuating) costs of fossil fuels. The world's oil-importing countries spent almost $1.5 trillion in 2007 and $2 trillion in 2008 to purchase crude oil whose imports create a permanent drag on balance of payments in many nations. Most notably, crude oil purchases cost the United States nearly $350 billion (16% of its total imports) in 2008 (USCB, 2009). Moreover, most of the remaining crude oil resources are in the notoriously unstable Middle East, and the past economic and military costs of safeguarding their production and delivery may pale compared to the investments, political concessions, and military interventions that may be required in the future.

Transition from an energy supply dominated by fossil fuels to a world relying mostly on non-fossil fuels and generating electricity by harnessing renewable energy flows is thus definitely desirable and, given the finite nature of fossil resources, it is eventually inevitable—but it is imperative to realize that the process will be considerably more difficult than is commonly realized. Five reasons explain the challenge: the overall scale of the coming shift, be it on the global level or in the world's largest economies; magnitudes of renewable energy resources and their surprisingly uneven distribution; the intermittent, and to a significant degree unpredictable, nature of most renewable energy flows; lower energy density of the fuels produced to replace solid and liquid fossil fuels; and, perhaps most importantly, substantially lower power densities with which we can harness renewable energies.

The scale of the coming energy transition is best illustrated by comparing the future demand for non-fossil fuels and primary electricity with the past demand for fossil energies that were needed to complete the epochal shift from biomass to coal and hydrocarbons. By the late 1890s, when the share of biomass energies slipped just below 50% of the world's total primary energy supply, less than 20 EJ of additional fossil fuel supply were needed to substitute all of the remaining biomass energy consumption. By 2010 the global use of fossil energies runs at the annual rate of roughly 400 EJ, which means that the need for new non-fossil energy supply to displace coal and hydrocarbons is 20 times greater in overall energy terms than was the need for fossil energies during the 1890s.

And the challenge is relatively even more daunting for all high-energy economies in general, and for the United States in particular. In 1884, when the U.S. primary energy supply was split between biomass and fossil fuels, the total energy demand was below 6 EJ, and hence only less than 3 EJ were needed to substitute the remaining biomass use (as already explained, this substitution never happened completely but by the year 2000 only 3% of U.S. commercial energy came from biomass). In contrast, recent U.S. energy demand has been approaching 100 EJ, of which only some 7% are now drawn from renewable energies (including hydroelectricity) and 8% from nuclear generation. This means that replacing all of America's fossil fuel demand will require about

85 EJ of additional non-fossil contributions, nearly 30 times the total of fossil fuels the country needed in the mid-1880s to complete its shift from biomass to coal and hydrocarbons.

There are nine major kinds of renewable energies: solar radiation; its six transformations as running water (hydro energy), wind, wind-generated ocean waves, ocean currents, thermal differences between the ocean's surface and deep waters, and photosynthesis (primary production); geothermal energy and tidal energy complete the list. As with fossil fuels, it is imperative to distinguish between renewable resources (aggregates of available fluxes) and reserves, their smaller (or very small) portions that are economically recoverable with existing extraction or conversion techniques. This key distinction applies as much to wind or waste cellulosic biomass as it does to crude oil or uranium, and that is why the often-cited enormous flows of renewable resources give no obvious indication as to the shares that can be realistically exploited.

Global reserves of renewable flows can be accurately determined only by careful assessment of regional and local limits, not by applying some generic fractions. For example, storing too much water for hydro generation could weaken many environmental services provided by flowing river water (including silt and nutrient transportation, channel cutting, and oxygen supply to aquatic biota), large-scale biofuel cultivation and repeated removal of excessive shares of photosynthetic production could further undermine the health of many natural ecosystems and agroecosystems by extending monocultures and opening ways for greater soil erosion and pest infestation, and harnessing significant shares of wind energy could affect regional climates and conceivably even the global air circulation.

Magnitude of annual flows (resources) of renewable energies is best appreciated by comparing them to the global extraction of fossil fuel that reached about 425 EJ or 13.5 TW in 2010. Solar radiation reaching the biosphere (after subtracting about 30% of the incoming radiation that is reflected by clouds and surfaces) amounts to 3.8 YJ or 120 PW, nearly four orders of magnitude greater than the annual fossil fuel consumption, and the total absorbed by land is roughly 790 ZJ or 25 PW, still nearly 2,000 times the current fossil fuel extraction. Even after excluding half of the terrestrial surfaces (polar and subpolar regions with the relatively weakest insolation, and the areas difficult to access, ranging from steep mountains to wetlands) as unsuitable location, there are still at least 15 PW of potentially usable flux, roughly a thousand times today's annual fossil fuel consumption.

Theoretically available wind resources are large but (as has been so well demonstrated with the harnessing of water power) only their small share will be practically exploitable. Peixoto and Oort (1992) estimated that about 870 TW of solar radiation (more than 60 times the current fossil flux) is transferred to wind's kinetic energy (and is dissipated as friction), and Archer and Jacobson (2005) put the accessible global wind flux at 80 m above ground at

72 TW. Lu, McElroy and Kiviluoma (2009) simulated global winds 100 m above ground and concluded that when using 2.5-MW turbines, excluding areas covered with ice, snow, forest, water and settlements, and assuming an average 20% capacity factor it could be possible to harness 78 TW.

How much of this theoretically available flux will be actually captured remains highly uncertain; a 10% share (about 7 TW) would be half of today's fossil fuel extraction. Potential energy of the global stream runoff adds up to nearly 10 TW, of which slightly more than 10% can be economically exploited by dams, and more than a third of that has been already harnessed. Wind-driven ocean waves have kinetic energy of some 60 TW of which only 3 TW (5%) are dissipated along the coasts. Ocean currents have power of at least 100 GW but only a very small part (on the order of a few GW) can be converted.

Tidal energy amounts to about 3 TW, of which only some 60 GW are dissipated in coastal waters. Ocean thermal gradient totals some 100 TW but because of the small temperature difference (maximum of about 20 K) its large-scale commercial use remains questionable. Terrestrial photosynthesis proceeds at a rate of nearly 60 TW, and even a tripling of biomass currently used for energy would not yield more than about 9 TW. Finally, the Earth's geothermal flux amounts to about 42 TW (Sclater, Jaupart, & Galson, 1980), but nearly 80% of that large total is through the ocean floor and all but a small fraction of it is a low-temperature diffuse heat. Available production techniques using hot steam could tap up to about 140 GW for electricity generation by the year 2050 (Bertani, 2009), and even if three times as much could be used for low-temperature heating the total would be less than 600 GW.

Reviewing the potentially usable maxima of renewable energy flows shows a sobering reality. First, direct solar radiation is the only form of renewable energy whose total terrestrial flux far surpasses not only today's demand for fossil fuels but also any level of global energy demand realistically imaginable during the twenty-first century (and far beyond). Second, only an extraordinarily high rate of wind energy capture (that may be environmentally undesirable and technically problematic) could provide a significant share of overall future energy demand. Third, for all other renewable energies maxima available for commercial harnessing fall far short of today's fossil fuel flux, one order of magnitude in the case of hydro energy, biomass energy, ocean waves, and geothermal energy, two orders of magnitude for tides, and four orders of magnitude for ocean currents and ocean thermal differences.

Consequently—and contrary to common perceptions of a cornucopia of renewable flows—there is only one kind of renewable energy that is so large that even the capture of a mere 0.1% of its land flux would satisfy global energy demand twice as large as the 2010 rate. Unfortunately, large-scale commercial conversions of that flux are still only in very early stages: In 2010 photovoltaic electricity generation produced still less than 0.1% of the world's electricity and, similarly, solar heating (mainly for household and commercial hot water supply) added less than 0.1% of the global primary energy supply. At the other end of the renewable spectrum are the four oceanic sources (waves, currents, temperature differences, and tides) with a very limited exploitable capacity, either due to their relatively minor aggregate flux or to difficulties in making their conversions economical in the foreseeable future (or both, as is the case of currents and thermal differences).

Biomass contributions could be increased by large-scale removal and conversion of waste (cellulosic) phytomass, mainly logging residues and cereal straws—but, once again, while this resource is large, its reserves (the share that can be repeatedly taken away without adverse effects) are limited. Logging residues from clear-cutting can yield a relatively high one-time harvest but those at remote sites and those left on steep slopes may not be economically recoverable and even the best efforts to collect the accessible resources may not gather more than half of the available wastes. And in most agroecosystems crop residues are a more valuable resource when they are recycled—in order to maintain soil's organic content, to retain moisture, and to prevent soil erosion—rather than when they are removed for fuel.

And while there is undoubtedly a very large theoretical potential for biomass harvested from new plantings of fast-growing trees and high-yielding grasses on currently unused land, those favoring such mega-planting schemes must first explain how they will supply the requisite water and macronutrients needed to sustain those plantings. Yet another proposal would cultivate nearly 90% of new energy crops on land that is now used for food production but that would be made superfluous by greatly increased efficiency of food cropping. One wishful assessment estimated the future biomass contribution at no less than about 365 EJ (nearly equal to all fossil fuels today) and it put the maximum potential by the year 2050 as high as 1.442 ZJ, more than three times today's total global energy use (Smeets et al., 2007). Improbability of this total led the authors themselves to admit that "such increases in productivity may be unrealistically high" (Smeets et al., 2007, p. 56)—but they use them anyway as the foundation for their meaningless claims.

Environmental impacts of large hydro energy projects have transformed their reputation from formerly desirable options to a highly questionable, and even a stridently opposed, form of renewable energy; in any case, even if all potentially suitable sites were to be developed, their electricity generation will remain a fraction of the coming global demand. Remaining hydro energy resources are also very unevenly distributed, with most of them in just a handful of countries (China, India, Russia, Congo, Brazil) and a similarly highly skewed spatial distribution is the norm, rather than an exception, for most of the renewable energy flows. Many regions (including the Mediterranean, Eastern Europe, large parts of Russia, Central Asia, Latin America, and Central Africa) have relatively low wind-generation potential (Archer & Jacobson, 2005); high geothermal gradients are concentrated along the ridges of major tectonic plates, above all along the Pacific Rim; and tidal power is dissipated mainly along straight coasts (unsuitable for tidal dams) and in regions with minor (<1 m) tidal ranges (Smil, 2008).

The third obvious fact complicating large-scale development of most of the renewable energy flows is their intermittency, some of which is perfectly predictable (daily availability of solar radiation in cloud-free subtropical settings; time and magnitude of local tides) but most of which can be only forecast with varying degrees of probability, particularly as far as longer term outlook is concerned (availability of solar radiation in cloudy mid-latitudes, timing and frequency of winds, seasonal harvests of phytomass affected by climate variations and pest infestations). There are two effective solutions for intermittency: storage in the case of fuels, and long-distance interconnections in the case of electricity generation.

Mass production of liquid biofuels fermented from annual harvests of crop or residual biomass would require large storages of either cereal or cellulosic feedstocks or the produced ethanol (or both), and the bulkiness of residues and relatively low energy densities of all of these materials would make such storages more costly than those of refined oils. New long-distance HV links will be appraised later in this chapter but they, too, would obviously entail significant initial infrastructural investment, a reality that militates against any rapid sustained contributions that renewable conversions sited in locations far away from major load centers could make to future energy balances.

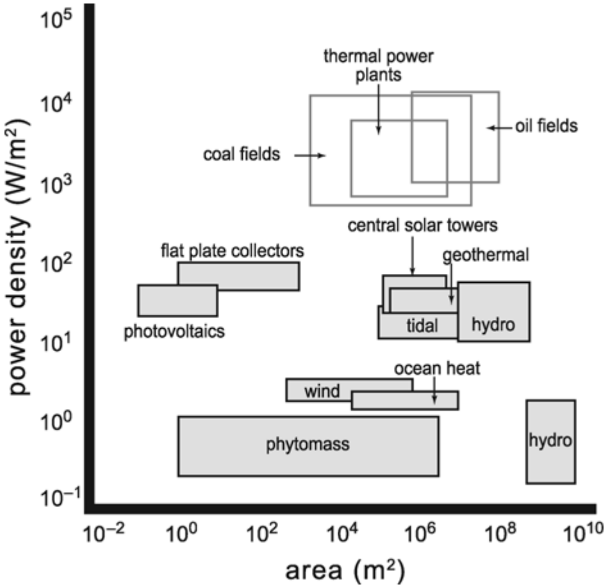
The fourth key consideration is that in terms of energy densities the coming shift will move the global energy system in the opposite, and less desirable, direction than did the epochal transition to fossil fuels that introduced fuels with superior energy densities: transition to non-fossil fuels rests on less energy-dense biofuels whose larger mass (for the equivalent energy supply) will require more handling and larger storages. As already explained (in chapter 1), even ordinary bituminous coal contains 30–50% more energy than air-dry wood, while the best hard coals are nearly twice as energy-dense as wood and liquid fuels refined from crude oil have nearly three times higher energy density than air-dry phytomass. A biomass-burning power plant would need a mass of fuel 30–50% larger than a coal-fired station of the same capacity. Similarly, ethanol fermented from crop carbohydrates has an energy density of 24 MJ/L, 30% less than gasoline (and biodiesel has an energy density about 12% lower than diesel fuel).

But lower energy density of non-fossil fuels is a relatively small inconvenience compared to inherently lower power densities of converting renewable energy flows into mass-produced commercial fuels or into electricity at GW scales. Power density is the rate of flow of energy per unit of land area. The measure is applicable to natural phenomena as well as to anthropogenic processes, and it can be used in revealing ways to compare the spatial requirements of energy harnessing (extraction, capture, conversion) with the levels of energy consumption. In order to maximize the measure's utility and to make comparisons of diverse sources, conversions, and uses my numerator is always in watts and the denominator is always a square meter of the Earth's *horizontal* area (W/m^2).

Others have used power density to express the rate of energy flow across a *vertical* working surface of a converter, most often across the plane of a wind turbine's rotation (the circle swept by the blades). When used that way, power density of a 3-MW Vestas machine (now a common choice for large wind farms) is roughly 400 W/m^2 and for the world's largest machine, ENERCON E-126 rated at 6 MW, it is 481 W/m^2. But because the turbines must be spaced at least three, and better yet five, rotor diameters apart in direction perpendicular to the prevailing wind and at least five, and with large installations up to ten, rotor diameters in the wind direction (in order to avoid excessive wake interference and allow for sufficient wind energy replenishment), power densities of wind generation are usually less than 10 W/m^2. Altamont Pass wind farm averages 3.5 W/m^2, while exceptionally windy sites may yield more than 10 W/m^2 and less windy farms with greater spacing may rate just above 1 W/m^2 (Figure 4.1).

Hydroelectricity will make important new contributions to the supply of renewable energy only in the modernizing countries of Asia, Africa, and Latin America. Because of their often relatively large reservoirs, smaller stations have power densities less than 1 W/m^2; for stations with installed capacities of

Figure 4.1 Power densities of renewable energy conversions, fossil fuel extraction, and thermal electricity generation. Plotted from data in Smil (2008).



0.5–1 GW the densities go up to about 1.5 W/m^2; the average power density for the world's largest dams (>1 GW) is over 3 W/m^2; the largest U.S. hydro station (Grand Coulee on the Columbia) rates nearly 20 W/m^2; and the world's largest project (Three Gorges station on the Chang Jiang) comes close to 30 W/m^2 (Smil, 2008). Power densities of hydro generation are thus broadly comparable to those of wind-driven generation, both having mostly magnitude of 10^0 W/m^2 and exceptional ratings in the lower range of 10^1 W/m^2 (Figure 4.1).

Typical power densities of phytomass fuels (or fuels derived by conversion of phytomass, including charcoal or ethanol) are even lower. Fast-growing willows, poplars, eucalypti, leucaenas, or pines grown in intensively managed (fertilized and if need be irrigated) plantations yield as little as 0.1 W/m^2 in arid and northern climates but up to 1 W/m^2 in the best temperate stands, with typical good harvests (about 10 t/ha) prorating to around 0.5 W/m^2 (Figure 4.1). Crops that are best at converting solar radiation into new biomass (C_4 plants) can have, when grown under optimum natural conditions and supplied by adequate water and nutrients, very high yields: National averages are now above 9 t/ha for U.S. corn and nearly 77 t/ha for Brazilian sugar cane (FAO, 2009). But even when converted with high fermentation efficiency, ethanol production from Iowa corn yields only about 0.25 W/m^2 and from Brazilian sugar cane about 0.45 W/m^2 (Bressan & Contini, 2007).

While the direct combustion of phytomass would yield the highest amount of useful energy, it is difficult to envisage the families in densely packed high-rises of Hong Kong, Mumbai, or São Paulo burning wood in small stoves. Realistic options would be the conversion of phytomass to electricity at large stations located near major plantations or the production of liquid or gaseous fuel: Such conversions would obviously lower the overall power density of the phytomass-based energy system (mostly to less than 0.3 W/m^2), require even larger areas of woody plantations, and necessitate major extensions of high-voltage transmission lines, and hence further enlarge overall land claims. Moreover, as the greatest opportunities for large-scale cultivation of trees for energy are available only in parts of Latin America, Africa, and Asia, any massive phytomass cultivation would also require voluminous (and energy-intensive) long-distance exports to major consuming regions.

And even if future bioengineered trees could be grown with admirably higher power densities (say, 2 W/m^2), their cultivation would run into obvious nutrient constraints. Non-leguminous trees producing dry phytomass at 15 t/ha would require annual nitrogen inputs on the order of 100 kg/ha during 10 years of their maturation. Extending such plantations to slightly more than half of today's global cropland would require as much nitrogen as is now applied annually to all food and feed crops—but the wood harvest would supply only about half of the energy that we now extract in fossil fuels. Other major environmental concerns include accelerated soil erosion (particularly before the canopies of many row plantations of fast-growing trees would close) and availability of adequate water supplies (Berndes, 2002).

Constraints are even more obvious as far as the substitution of refined oil products is concerned. Even if all of the world's sugar cane crop were converted to ethanol, the annual ethanol yield would be less than 5% of the global gasoline demand in 2010. Even if the entire U.S. corn harvest was converted to ethanol, it would produce an equivalent of less than 15% of the country's recent annual gasoline consumption. Biofuel enthusiasts envisage biorefineries using plant feedstocks that replace current crude oil refineries—but they forget that unlike the highly energy-dense oil that is produced with high power density, biomass is bulky, tricky to handle, and contains a fairly high share of water.

This makes its transport to a centralized processing facility uneconomical (and too energy intensive) beyond a restricted radius (maximum of about 80 km) and, in turn, this supply constraint limits the throughput of a biorefinery and the range of fuels to be produced—to say nothing about the yet-to-be-traversed path from laboratory benches to mass-scale production (Willems, 2009). A thoughtful review of biofuel prospects summed it up well: They can be an ingredient of the future energy supply but "realistic assessments of the production challenges and costs ahead impose major limits" (Sinclair, 2009, p. 407).

And finally, the proponents of massive biomass harvesting ignore a worrisome fact that modern civilization is already claiming (directly and indirectly) a very high share of the Earth's net terrestrial primary productivity (NPP), the total of new phytomass that is photosynthesized in the course of a single year and that is dominated by the production of woody tissues (boles, branches, bark, roots) in tropical and temperate forests. Most of this photosynthate should be always left untouched in order to support all other nonhuman heterotrophs (from archaea and bacteria to primates) and to perform, directly or indirectly via the heterotrophs, numerous indispensable environmental services.

Given this fact it is astonishing, and obviously worrisome, that three independently conducted studies (Vitousek et al., 1986; Rojstaczer, Sterling, & Moore, 2001; Imhoff et al., 2004) agree that human actions are already appropriating perhaps as much as 40% of the Earth's NPP as cultivated food, fiber, and feed, as the harvests of wood for pulp, timber, and fuel, as grass grazed by domesticated animals, and as fires deliberately set to maintain grassy habitats or to convert forests to other uses. This appropriation is also very unevenly distributed, with minuscule rates in some thinly populated areas of tropical rain forests to shares in excess of 60% in East Asia and to more than 70% in Western Europe (Imhoff et al., 2004). Local rates are even higher in the world's most intensively cultivated agroecosystems of the most densely populated regions of Asia (China's Jiangsu, Sichuan, and Guangdong, Indonesia's Java, Bangladesh, the Nile Delta).

Any shift toward large-scale cultivation/harvesting of phytomass would push the global share of human NPP appropriation above 50% and would make many regional appropriation totals intolerably high. There is an utter disconnect between the proponents of transition to mass-scale biomass use and the ecologists whose Millennium Ecosystem Assessment (2005) demonstrated that essential ecosystemic services that underpin the functioning of all economies have been already modified, reduced, and compromised to a worrisome degree. Would any of numerous environmental services provided by diverse ecosystems—ranging from protection against soil erosion to perpetuation of biodiversity—be enhanced by extensive cultivation of high-yielding monocultures for energy? I feel strongly that the recent proposals of massive biomass energy schemes are among the most regrettable examples of wishful thinking and ignorance of ecosystemic realities and necessities.

Phytomass would have a chance to become, once again, a major component of the global primary energy supply only if we were to design new photosynthetic pathways that did not emerge during hundreds of millions of years of autotrophic evolution or if we were able to produce fuels directly by genetically manipulated bacteria. The latter option is now under active investigation, with Exxon being its most important corporate sponsor and Venter's Synthetic Genomics its leading scientific developer (Service, 2009). Overconfident gene manipulators may boast of soon-to-come feats of algally produced gasoline, but how soon would any promising yields achieved in controlled laboratory conditions be transferable to mass-scale cultivation?

As always in global energy supply, the scale matters: A laboratory bioreactor yields a few liters of a product per day, but if we were to replace half of liquid fuels refined from crude oil with algal hydrocarbons our daily output would have to be on the order of seven billion liters, and ranging from light (gasoline-like) to heavy (residual fuel-like) fraction. And maximized and highly targeted algal photosynthesis will be always predicated on maintaining many environmental optima, namely those of water temperature (minimal fluctuation around a species-specific preference), water oxygen concentration, pH, alkalinity, light intensity, and plant density (high densities depress photosynthesis) and on providing adequate nutrients: Naturally, a great deal of energy would be required to operate such high-throughput cultivation. These realities make it clear that even if we already had superior hydrocarbon-producing algae their adoption as a globally important component of primary energy supply would not be a matter of a decade or two.

We thus come back to direct solar radiation as the only renewable energy flux distinguished not only by its abundance but also by its relatively high power density. No other renewable energy flux comes even close to the amount of solar radiation reaching the Earth at such a relatively high power density—and that density of capture could increase by an order of magnitude if we could harness sunlight in space, a concept that goes back to Glaser (1968), or on the lunar surface (Criswell, 2000) and beam the microwave energy back to the Earth.

These are conceptually very rational proposals—but with no chance of large-scale commercialization during the coming generation or two (although in 2009 Space Energy company claimed it will go commercial in 10 years).

Solar radiation reaching the ground has the highest flux in cloud-free subtropics; for example, in northeastern Saudi Arabia the maximum power densities are more than 1,100 W/m^2 during the peak insolation hours and the highest daily means go up to 350 W/m^2 (Sahin, Aksakal, & Kahraman, 2000). Annual continental average has the global mean of about 170 W/m^2 and the oceanic means is slightly higher at 180 W/m^2. Average insolation densities of 10^2 W/m^2 mean that even with today's relatively low-efficiency PV conversions (the best rates in everyday operation are still below 20%) we can produce electricity with power densities of around 30 W/m^2, and if today's best experimental designs (multijunction concentrators with efficiency of about 40%) become commercial realities we could see PV generation power densities averaging more than 60 W/m^2 and surpassing 400 W/m^2 during the peak insolation hours.

As impressive as that would be, fossil fuels are extracted in mines and hydrocarbons fields with power densities of 10^3–10^4 W/m^2 (i.e., 1–10 kW/m^2), and the rates for thermal electricity generation are similar (see Figure 4.1). Even after including all other transportation, processing, conversion, transmission, and distribution needs, power densities for the typical provision of coals, hydrocarbons, and thermal electricity generated by their combustion are lowered to no less than 10^2 W/m^2, most commonly to the range of 250–500 W/m^2. These typical power densities of fossil fuel energy systems are two to three orders of magnitude higher than the power densities of wind- or water-driven electricity generation and biomass cultivation and conversion, and an order of magnitude higher than today's best photovoltaic conversions.

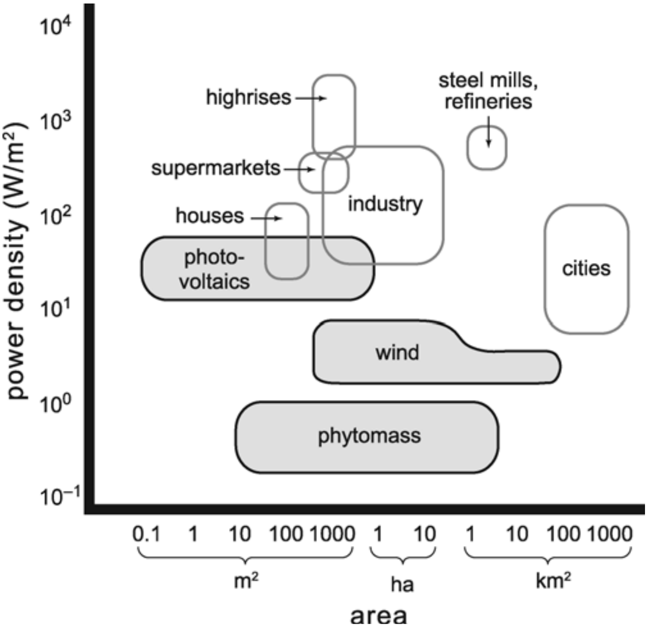
I have calculated that in the early years of the twenty-first century no more than 30,000 km^2 were taken up by the extraction, processing, and transportation of fossil fuels and by generation and transmission of thermal electricity (Smil, 2008). Spatial claim of the world's fossil fuel infrastructure is thus equal to the area of Belgium (or, even if the actual figure is up to 40% larger, to the area of Denmark). But if renewable energy sources were to satisfy significant shares (15–30%) of national demand for fuel and electricity, then their low power densities would translate into very large space requirements—and they would add up to unrealistically large land claims if they were to supply major shares of the global energy need.

Even if we assume (quite optimistically) that the cultivation of phytomass for energy could average 1 W/m^2, then supplanting today's 12.5 TW of fossil fuels would require 12,500,000 km^2, roughly an equivalent of the entire territories of the United States *and* India, an area more than 400 times larger than the space taken up by all of modern energy's infrastructures. If only half of today's fossil fuel consumption were replaced by woody biomass, its plantations would require an area a bit larger than that of all existing forests in North America.

Low extraction power densities would be the greatest challenge in producing liquid fuels from phytomass. If all of America's gasoline demands were to be derived from corn-based ethanol, the crop would have to be grown on an area roughly 20% larger than is the country's total arable land. And land claims of corn-based ethanol would be much worse outside the United States: Global corn-yield averages only a bit more than half of the U.S. mean.

At the same time, energy is consumed in modern urban and industrial areas at increasingly higher power densities, ranging from less than 10 W/m^2 in sprawling cities in low-income countries (including their transportation networks) to 50–150 W/m^2 in densely packed high-income metropolitan areas and to more than 500 W/m^2 in downtowns of large northern cities during winter (Smil, 2008). Industrial facilities, above all steel mills and refineries, have power densities in excess of 500 W/m^2 even prorated over their entire fence area—and high-rise buildings that will house an increasing share of humanity in the twenty-first century megacities go easily above 1,000 W/m^2. This mismatch between the inherently low power densities of renewable energy flows and relatively high power densities of modern final energy uses (Figure 4.2) means that a solar-based system will require a profound spatial restructuring with major environmental and socioeconomic consequences.

Figure 4.2 Power densities of renewable conversions and typical industrial, urban, and household energy uses. Plotted from data in Smil (2008).



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In order to energize the existing residential, industrial, and transportation infrastructures inherited from the fossil-fuel era, a solar-based society would have to concentrate diffuse flows to bridge power density gaps of two to three orders of magnitude. Mass adoption of renewable energies would thus necessitate a fundamental reshaping of modern energy infrastructures, from a system dominated by global diffusion of concentrated energies from a relatively limited number of nodes extracting fuels with very high power densities to a system that would collect fuels of low energy density at low power densities over extensive areas and concentrate them in the increasingly more populous consumption centers. This is not impossible, but the challenges of this massive infrastructural reorganization should not be underestimated, and the tempo of this grand transformation would have to be necessarily slow. But, given our new high-tech prowess, could not these processes be accelerated, could not faster rates of coming energy transitions turn all past experiences into irrelevant examples of only a limited historical interest?

PACE OF TRANSITIONS: INNOVATION, INFRASTRUCTURES, AND INERTIA

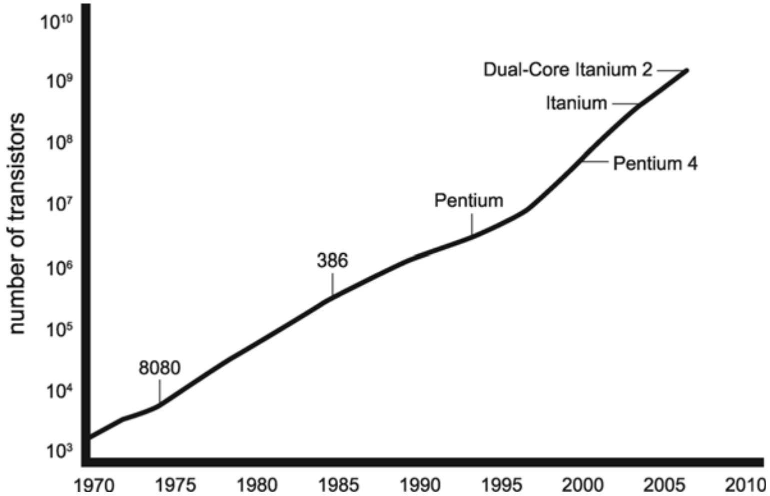
I must address first an important notion of accelerating technical advances and then look at more reasons why the coming transition from a system dominated by conversions of fossil fuels to a new arrangement relying on non-fossil energies, and mostly on harnessing renewable resources, will be more difficult than is commonly realized. Not surprisingly, the notion of generally accelerating pace of technical innovation has been driven primarily by some admirable advances in computing capacities. Extending this undeniable specific reality to a generally applicable conclusion is a clear *pars pro toto* error. Some of its expressions are truly breathtaking: According to Ray Kurzweil (a leading techno-enthusiast eager to elevate the past computing experience to a universal norm), the twentieth century was "equivalent to 20 years of progress at today's rate of progress . . . and because of the explosive power of exponential growth, the 21st century will be equivalent to 20,000 years of progress at today's rate of progress" (Kurzweil & Meyer, 2003, p. 2).

And—as attested by the existence of the Accelerating Innovation Foundation, the Center for Accelerating Innovation, and the Institute for Accelerating Change—Kurzweil's is hardly an isolated belief. Perhaps nothing expressed the hoped-for impact that this acceleration is to have on the coming energy transition than former Vice President Al Gore's appeal for repowering U.S. electricity generation in a single decade. In his speech on July 17, 2008, Gore repeated a standard mantra that "as the demand for renewable energy grows, the costs will continue to fall" and he illustrated the expected price declines with what he called one revealing example, the price of specialized silicon used to make solar cells that "was recently as high as $300 per kilogram. But the newest contracts have prices as low as $50 a kilogram." Then he continued: "You know, the same thing happened with computer chips—also made out of silicon. The price paid for the same performance came down by 50 percent every 18 months—year after year, and that's what's happened for 40 years in a row" (Gore, 2008, p. 6).

There are two fundamental problems with this unfortunate comparison. Steadily rising performance of microprocessors (chips) has hardly anything to do (as implied by Gore: "also made out of silicon") with any declines in price of silicon. True, that exacting process of producing extremely pure polycrystalline silicon and converting it into crystals that are sliced into thin wafers has become less expensive over time—but a blank silicon wafer represents only about 2% of the total value of a finished microprocessor. That phenomenal increase in microchip performance (and hence a huge drop in cost per unit operation) has been due overwhelmingly to the ability of crowding more transistors on the miniature wafer (Smil, 2006). In 1965, when the early integrated circuits contained just 50 transistors, Gordon Moore predicted that their density will be doubling every 12 months (Moore, 1965), and 10 years later he lengthened the doubling period to two years.

The world's first universal microprocessor, released by Intel in November 1971, had 2,250 metal oxide semiconductor transistors (Mazor, 1995). By 2009 their highest count on central processing units surpassed 1 billion, the result of 19 consecutive doublings. For nearly four decades Moore's law has stood the test of time (or Intel's efforts have made it a self-fulfilling prophecy) and its relentless progress has brought the combination of exponentially rising performance of microprocessors, their increasing affordability, and their still expanding applications, including in all important processes of energy extraction, harnessing, and conversion (Figure 4.3).

Figure 4.3 Moore's law. Plotted from data in Intel (2003, 2007).



Microprocessors have made exploration, production, and conversion of energy easier, more reliable, and more efficient, but their use has not changed the fundamental parameters of these established procedures and techniques. This contrast underscores the fact that an ever-denser packing of transistors on microchips has been an exceptional case of technical progress and that the advances in energy extraction, harnessing, and conversion have not been governed by rapid doublings of performances accompanied by relentless decline in prices. Even if Moore's average doubling period were relaxed and doubled to four years, we still could not find any established energy production or conversion technique that would have followed such a path of improving performance coinciding with the microchip era that began in 1971.

Even the most rapid past transitions to more efficient energy converters and to more powerful prime movers did not come anywhere close to the rates dictated by Moore's law. For example, the largest marine diesel engines increased their power rating about six-fold between 1950 and the year 2000, while gas turbines in flight increased their maximum power roughly ten-fold in 25 years, from de Havilland's Ghost engine with thrust of 22 kN in 1945 to Pratt & Whitney's JT9D with the thrust of 210 kN certified in 1969 (Smil, 2010b). More importantly, for some basic energy production processes and conversions—be it surface extraction and unit train transportation of coal, crude oil shipment by tankers and the fuel's processing in refineries, turbogenerators in thermal power plants, or long-distance transmission voltages—there have been either no, or only marginal, gains in the best performance or in maximum ratings and unit capacities during the past four decades.

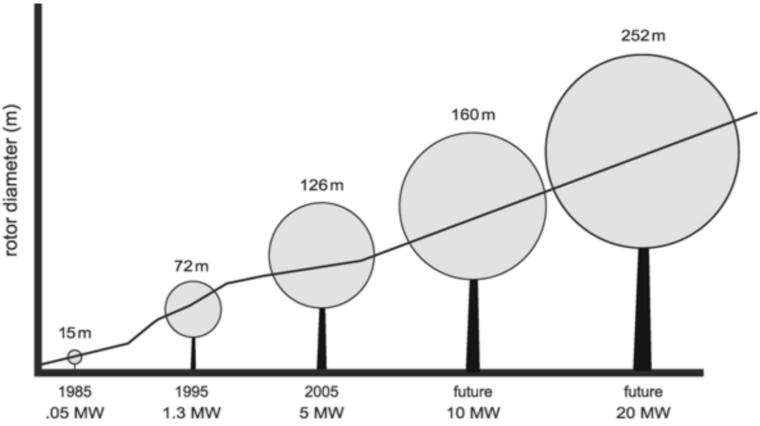
Perhaps the most important case of this technical stasis has been the efficiency of thermal generation, now the source of four-fifths of the world's electricity. Capacity of typical steam turbo-generating units has been stagnant since the early 1970s and both the maximum and average efficiency of fossil-fueled power plants have not improved since the early 1960s (Yeh & Rubin, 2003; EIA, 2009). U.S. statistics show average consumption of 11.1 MJ/kWh in 1970 and 10.9 MJ/kWh in 2000, a tiny 2% gain in three decades. Unfortunately, there are no parallels between rising microchip capacities and improving performance of energy conversions, and the idea of accelerating technical progress does not apply to any fundamental advances in energy harnessing and use.

But should not this conclusion be questioned by pointing out that it has been based on the advances of long-established, and hence obviously mature, techniques and that innovative conversions of renewable energies that are on thresholds of mass markets will behave differently? The best way to appraise their past progress and near-term potential is to focus on the two most promising new energy conversions, on wind-driven and photovoltaic electricity generation. Commercialization of large wind turbines has shown notable capacity advances and engendered high expectation. In 1986 California's Altamont Pass, the first large-scale modern wind farm, whose construction began in the 1981, had average turbine capacity of 94 kW and the largest units rated 330 kW (Smith, 1987). Nearly 20 years later the world's largest turbine rated 6 MW and typical new installations were 1 MW.

This means that the modal capacities of wind turbines have been doubling every 5.5 years (they grew roughly ten-fold in two decades) and that the largest capacities have doubled every 4.4 years (they increased by a factor of 18 in two decades). Even so, these highest unit capacities are two orders of magnitude smaller than the average capacities of steam turbogenerators, the best conversion efficiencies of wind turbines have remained largely unchanged since the late 1980s (at around 35%), and neither they nor the maximum capacities will see several consecutive doublings during the next 10–20 years. The EU's UpWind research project has been considering designs of turbines with capacities between 10 and 20 MW whose rotor diameters would be 160–252 m, the latter dimension being twice the diameter of a 5-MW machine and more than three times the wing span of the jumbo A380 jetliner (UpWind, 2009; Figure 4.4).

Hendriks (2008) argues that building such structures is technically possible, because the Eiffel tower had surpassed 300 m already in 1889 and because we routinely build supertankers and giant container vessels whose length approaches 400 m, and assemble bridges whose individual elements have mass more than 5,000 t. That this comparison is guilty of a categorical mistake (as none of those structures is surmounted by massive moving rotors) is not actually so important: What matters are the economies of such giant turbines and, as Bulder (2009) concluded, those are not at all obvious. This is mainly because the weight stresses are proportional to the turbine radius (making longer blades more susceptible to buckling) and because the turbine's energy yield goes up with the square of its radius while the mass (i.e., the turbine's cost) goes up with the cube of the radius.

Figure 4.4 Increasing rotor diameter of the largest wind turbines (1985–2010) compared with a diameter of a 20-MW machine. Adapted from UpWind (2009).



But even if we were to see a 20-MW machine as early as 2020 this would amount to just a tripling of the maximum capacities in a decade, hardly an unprecedented achievement: For example, average capacities of new steam turbogenerators installed in U.S. thermal stations rose from 175 MW in 1960 to 575 MW in 1970, more than a threefold gain. And it is obvious that no wind turbine can be nearly 100% efficient (as natural gas furnace or large electric motors now routinely are), as that would virtually stop the wind flow, and a truly massive deployment of such super-efficient turbines would drastically change local and regional climate by altering the normal wind patterns. The maximum share of wind's kinetic energy that can be converted into rotary motion occurs when the ratio of wind speed after the passage through the rotor plane and the wind speed impacting the turbine is 1/3 and it amounts to 16/27 or 59% of the wind's total kinetic energy (Betz, 1926). Consequently, it will be impossible even to double today's prevailing wind turbine efficiencies in the future.

And Gore's silicon analogy is no less flawed when applied to PV generation, a technique whose major applications have been actually based on silicon wafers. True, the cost of producing PV cells has declined substantially—from $100/W in 1970 to about $1/W—and this trend has been sufficiently impressive to engender expectations of further cost declines and to foresee an early arrival of grid-parity when the cost of decentralized PV generation will equal the cost of electricity delivered by the existing grid with electricity generated largely from the combustion of fossil fuel. Again, corrective perspectives are in order. While some producers can now turn out their cells at $1/W, the average U.S. retail price of complete PV modules was $4.60/W in 2009, and this price represented just over half of the total retail cost for a residential rooftop PV system (about $8.75/W in 2009), with balance of the system and installation accounting for most of the remainder (Solarbuzz, 2009).

If the cost of complete PV modules were to be halved every 18 months then in just 10 years it would drop to 1% of today's value and the modules selling for close to $5/W would cost less than $0.05/W, and they would be producing the cheapest electricity in history. That is, obviously, quite impossible, and the PV industry's more realistic expectations are to reduce the price of typical modules to $1.5–2/W within 10 years, implying a halving of the cost in seven to eight years. But this does not mean that the cost of actual PV installations will be halved as well, because the costs of other components (inverters and regulators) and the cost of installation may not fall that fast. After all, despite the falling costs of PV cells, the cost of electricity generated by typical residential systems (with capacities of about 2 kW) has hardly changed since the year 2000, when it was close to 40 cents/kWh: During the second half of 2009 it was still between 35 and 36 c/kWh. And even the largest industrial installations (up to 500 kW) were generating electricity in 2009 almost as expensively as in 2000 at 19–20 c/kWh (Solarbuzz, 2009).

Moreover, if there is to be early grid parity for decentralized PV systems then the total installed module cost of $8.75/W in 2009 would have to fall to about $2/W and the overall cost of producing PV cells would have to be just around $1/W. But because in the past each doubling of cumulative production volume reduced the module costs by some 20%, nearly seven doublings (more than 100-fold volume increase) would be needed to bring today's price to that level. And this would not suffice, as we would also have to assume that the non-PV costs would be declining at a comparable rate, a clearly optimistic assumption, especially as far as the cost of installation and maintenance labor is concerned.

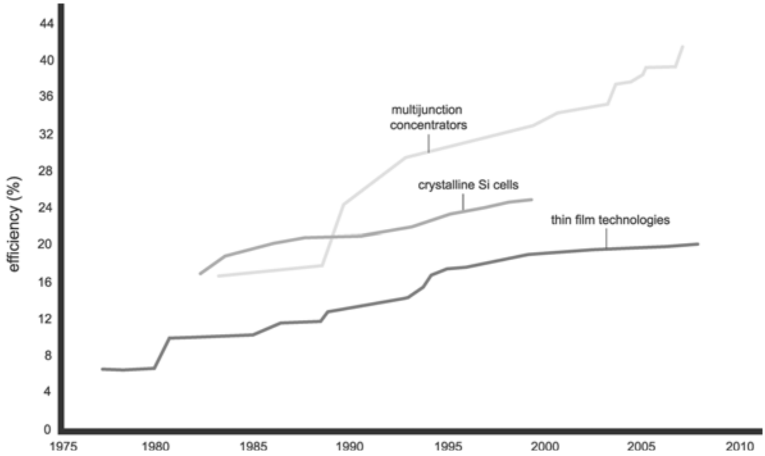
In any case, even the most enthusiastic advocates of PV electricity do not envisage a 100-fold rise in cumulative installations in a matter of years, and slower rates of cost decline would defer the time of grid parity, and hence the real beginning of large-scale diffusion of PV generation, until after 2020 or 2025. However, Yang (2010) uses the history of solar hot water systems to argue that even at that point the diffusion of decentralized rooftop PV installations may be relatively slow. Solar hot water systems have been cost-effective (saving electricity at a cost well below grid parity) in sunny regions for decades, and with nearly 130 GW installed worldwide they are clearly also a mature innovation—and yet less than 1% of all U.S. households have chosen to install them (Davidson, 2005).

The most obvious explanation is that for most consumers the long-term savings are not significant enough to justify a relatively high initial capital investment and to purchase and maintain another energy delivery system that would supplement only one function served by the existing electricity connection. If solar hot water systems are a valid indicator, then the adoption of decentralized PV generation may proceed even slower because its initial capital costs are much higher and because of the necessity to integrate these installations with the existing grid. And even more fundamentally, performance of commercially deployed PV cells has not been soaring, with efficiencies of thin-film cells doubling between 1980 and 1995 (from 8% to 16%) but remaining below 20% by 2009, while the efficiency of multijunction concentrating monocrystalline cells rose from about 30% in 1995 to about 40% by the year 2008 (NREL, 2009; Figure 4.5).

This means that even the best conversions in research laboratories have required 15–20 years to double their efficiency and that another doubling for multijunction and monocrystalline cells is highly unlikely. Similarly, fundamental physical and biochemical limits restrict the performance of other renewable energy conversions, be it the maximum yield of crops grown for fuel or woody biomass or the power to be harnessed from waves or tides: These limits will assert themselves after only relatively modest improvements of today's performance and hence no strings of successive performance doublings are ahead.

Any expectations that the future performance gains of renewable energies in general, and solar PV electricity generation in particular, will resemble the

Figure 4.5 Maximum efficiencies of PV cells achieved in laboratories. Plotted from data in NREL (2009).



post-1971 record of packing transistors on microchips are thus a consequence of succumbing to what I have called Moore's curse, an unfortunate categorical mistake that takes an exceptional performance as a general norm of coming technical innovation. The second key reason why the doubling of microprocessor performance every two years is an entirely inappropriate analogy for assessing the future of renewable energy conversions is that such a comparison completely ignores the need for massive infrastructures to extract, harness, process, transport, and convert energies.

Production of microprocessors is a costly activity, with the fabrication facilities costing at least $2–3 (and future ones up to $10) billion. But given the entirely automated nature of the production process (with microprocessors used to design more advanced fabrication facilities) and a massive annual output of these factories, the entire world can be served by only a small number of chip-making facilities. Intel, whose share of the global microprocessor market remains close to 80%, has only 15 operating silicon wafer fabrication facilities in nine locations around the world, and two new units under construction (Intel, 2009), and worldwide there are only about 300 plants making high-grade silicon. Such an infrastructural sparsity is the very opposite of the situation prevailing in energy production, delivery, and consumption.

Coal and uranium mines, oil and gas fields, coal trains, pipelines, coal-carrying vessels, oil and LNG tankers, coal treatment plants, refineries, LNG terminals, uranium processing (and reprocessing) facilities, thermal and hydro electricity-generating plants, HV transmission lines and distribution lines, and gasoline and diesel filling stations constitute the world's most extensive, and the most costly, web of infrastructures that now spans the globe. Its individual components number between thousands (large coal mines and large thermal power plants) and tens of thousands of facilities (there are about 50,000 oil fields) and its worldwide networks extend over millions of kilometers: For example, the United States alone has about 300,000 km of oil and 500,000 km of natural gas pipelines as well as some 300,000 km of transmission lines (Smil, 2008).

These infrastructures are present in high densities in all affluent nations, and modernizing countries are building them as rapidly as they can. Certainly the most impressive example is China's coal-based quest for modernity. During the first eight years of the twenty-first century China more than doubled its coal extraction and it added almost 300 GW of new coal-fired electricity-generating capacity, more than the combined thermal-generating capacity installed in the EU's five largest economies (Germany, France, the United Kingdom, Italy, and Spain) by 2006 (EIA, 2008). Even by using a very conservative cost average of $1,000/kW the latter building spree represents an investment on the order of $300 billion and these plants will operate for at least 30–35 years to recover their cost and to make profit.

Could anybody expect that the Chinese will suddenly terminate this brand-new investment and turn to costlier methods of electricity generation that remain relatively unproven and that are not readily available at GW scale? In global terms, could we expect that the world will simply walk away from fossil and nuclear energy infrastructures whose replacement cost is worth at least $15–20 trillion before these investments will be paid for and produce rewarding returns? Negative answers to these questions are obvious. But the infrastructural argument cuts forward as well because new large-scale infrastructures must be put in place before any new modes of electricity generation or new methods of producing and distributing biofuels can begin to make a major difference in modern high-energy economies. Given the scale of national and global energy demand (for large countries 10^{11} W, globally nearly 15 TW in 2010, likely around 20 TW by 2025) and the cost and complexity of the requisite new infrastructures, there can be no advances in the structure and function of energy systems that are even remotely analogical to Moore's progression of transistor packing.

Given these realities it is not at all surprising that the actual advances of renewable conversions have not been exceptionally rapid. In global terms the new renewables—wind, geothermal, solar (both thermal and PV), and modern biofuels—contributed no more than 0.45% of all primary energy in 1990 and by 2008 that share rose to about 0.75%. In relative terms this translates to an annual exponential growth of 2.85%, a much slower expansion than during the early decades of coal mining (more than 5%/year between 1850 and 1870), oil extraction (more than 8%/year between 1880 and 1900), or natural gas production (more than 6%/year between 1920 and 1940). And while in relative terms this was a considerably faster growth rate than those of expanding coal, crude oil, and natural gas production during the same period (their multiples were, respectively, 1.56, 1.48, and 1.24), in absolute terms it amounted to adding an equivalent of about 50 Mtoe in 18 years while during the same period coal production added about 1,080 Mtoe, oil extraction added about 760 Mtoe, and natural gas production increased by nearly 990 Mtoe.

Fossil fuel additions during that period thus amounted to about 2.83 Gtoe and they were roughly 57 times higher than the gain for all new renewables. Jefferson (2008) calls this rightly a very poor performance, but the contrast is not so surprising when the first (already outlined) challenge of the coming transition—the magnitude of the global switch from fossil to renewable energies—is kept in mind. The achievement is, obviously, better as far as electricity is concerned, but even in that case the aggregate share for wind, geothermal, PV, and biomass-fueled generation reached just 3% of the total in 2008, wind generation accounting for half of that fraction, and with solar electricity remaining below 0.05% of the total.

Finally, I must emphasize the relatively slow rates of past and present transitions to new prime movers. This was the case for replacing draft animals by machines even in the United States, where it had taken more than half a century to complete the transition from horses and mules to tractors and combines to internal combustion engines. Less surprisingly, poverty explains why the transition from animate to inanimate prime movers in agriculture is yet to be completed in many low-income nations: There are still some 500 million draft oxen, buffaloes, horses, donkeys, and camels, most of them in Asia and Africa. On national scales their aggregate capacity (roughly 200 GW) has become dwarfed by the power of agricultural machinery tractors and pumps but their work remains indispensable in many rural regions not only for field work but also for local transportation.

Inertial reliance on the first mechanical prime mover is best illustrated by a wartime example. By the time the Japanese attacked Pearl Harbor in December 1941 there could be absolutely no doubt about the superiority of diesel engines in marine propulsion: First small ship engines were installed on river-going vessels in 1903, the first diesel-powered vessel completed its intercontinental voyage in 1911, and by 1940 a quarter of the world's merchant fleet, and practically all newly launched ships, had diesel engines (Smil, 2010b). But when the U.S. military needed the fastest possible delivery of a large number of transport ships the choice was made to go with steam propulsion. Between 1942 and 1945 U.S. and Canadian shipyards built 2,710 *Liberty* (EC2) class ships powered by three-cylinder steam engines (each supplied by two oil-fired boilers) rated at 1.86 MW (Bunker, 1972; Elphick, 2001). The "ships that won the war" thus used the prime mover introduced during the 1770s and perfected during the subsequent 100 years.

As already explained (in chapter 2), the world's currently most numerous fuel-powered prime movers are internal combustion engines, gasoline-fueled sparking engines in passenger cars and light trucks, and diesel engines in cars, heavy trucks, trains, ships, and heavy machinery. By 2010 the aggregate count of these machines reached one billion and their installed capacity surpassed 150 TW. Their remarkable inertia is illustrated by recalling that their first prototypes were deployed in Germany during the mid-1880s (gasoline engines built by Benz, Maybach, and Daimler) and the late 1890s (Diesel's engine), that their commercialization was well underway before World War I, and that their technical maturity was reached shortly after World War II with designs in the United States, Europe, and Japan. The engine's two currently most prominent innovative modifications—a hybrid arrangement that couples it with electric motors, and so-called Dies-Otto engine that combines its standard (sparking) operation with that of a (non-sparking) Diesel machine—do not fundamentally alter its basic design.

The only emerging rival of gasoline and diesel engines is the all-electric drive, but a long history of electric cars and repeated delays of their mass adoption make an imminent demise of the gasoline-fueled internal combustion engine highly unlikely. Technical breakthrough of another alternative, the fuel cell–powered drive, was prematurely touted as imminent during the late 1990s but the probability of near-term large-scale commercial adoption of vehicles powered by hydrogen remains exceedingly low. An even more unlikely event is any early replacement of massive diesel engines that are used in heavy-duty road and rail transport and that almost completely dominate high-volume ocean shipping: There is simply no alternative to the machine, as no existing combustion engine can deliver the same service at a comparable cost and, no less importantly, at a similarly high reliability and durability.

Finally, most people would not think of steam turbines when asked to name the world's most important continuously working prime mover. The machine was invented by Charles Parsons in 1884, it was much improved and widely commercialized before World War I, and it has remained fundamentally unchanged 125 years later: Gradual advances in metallurgy made it simply larger and more efficient, but their pace has slowed significantly since the late 1960s and the early 1970s when it reached its highest unit capacities in excess of 1 GW. The position of steam turbines as the world's most powerful stationary prime mover is solidly entrenched: These machines now generate more than 70% of the world's electricity in fossil-fueled and nuclear stations (the rest comes from gas and water turbines and diesels) and there is simply no alternative technique of a similar capacity, efficiency, and reliability in sight. And there are no prospects for any near-term replacement of gas turbines used in flight: There is simply no alternative to replace these prime movers that have dominated global air transportation since the 1960s.

Without any doubt, our reliance on those indispensable prime movers introduced, respectively, during the 1880s, 1890s, and 1930s is even more inertial than our dependence on primary energies: Transition spans for fuels are measured in decades, while generations (a single generation being a span of 20–30 years) may be a better choice for the prime movers. As a result the principal impact of renewable energy conversions on transportation will be limited for many decades to producing alternative fuels to be used by internal combustion engines and perhaps also by natural gas turbines in flight. But, as already explained, an even relatively modest contribution by liquid biofuels (up to 20% of today's global demand for gasoline, kerosene, diesel, and residual oils) would have enormous impacts on agroecosystems, on fertilizer and energy demand and costs, and on world food prices.

NATIONAL ASPIRATIONS: GOALS AND REALITIES

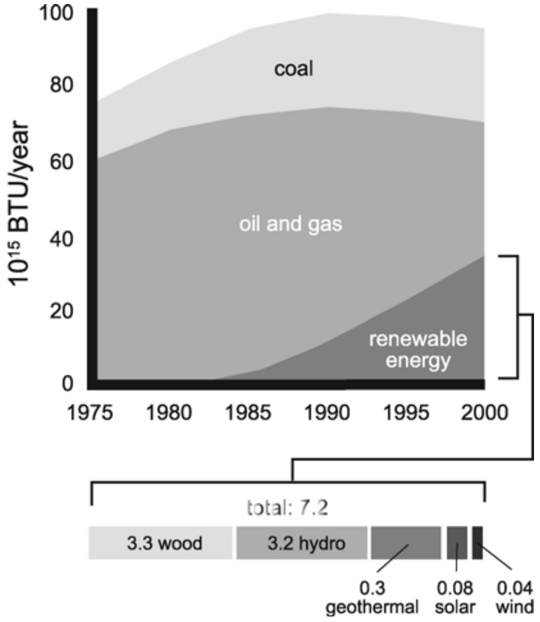
Substitution goals are usually stated as shares of a particular energy supply to be provided by specified new energy conversions in future years (typically ending in zero or five) and are accepted by governments, although not necessarily as binding targets. Aspirations and perceived potentials are expressed in formal and informal forecasts, proposals, and scenarios produced by governments, industrial associations, nongovernmental organizations, and universities, and by frequent promises of campaigning politicians. Most of these goals and aspirations share a basic property, namely that they do not dwell on all those sobering, limiting, and complicating realities that were explained in the first two sections of this chapter.

Robust optimism (or, less charitably, naïve expectations) and a remarkable unwillingness to err on the side of caution is an unmistakable commonality shared by an overwhelming majority of those goals, promises, and aspirations. This, of course, is nothing new. Recent anticipations of a fairly rapid and comfortingly smooth transition to renewable energies had a notable precedent during the aftermath of the first two energy "crises" (1973–1974 and 1979–1981) when those large, OPEC-driven increases in oil prices convinced many people that the end of the hydrocarbon era was imminent and that a grand transition to renewable was about to begin.

Among many failed forecasts from that era is the InterTechnology Corporation's (1977) conclusion that by the year 2000 solar energy could provide 36% of U.S. industrial process heat; Sørensen's (1980) disaggregation that put the share of U.S. renewable energy in 2005 at 49%, with biogas and wind each at 5%; and Lovins's forecast of more than 30% renewables in 2000. Actual share of all renewables in the U.S. 2000 primary energy supply was about 7%, with biogas supplying less than 0.001%, wind 0.04%, photovoltaics less than 0.1%, and there was no use of solar energy for industrial heat supply (Figure 4.6).

But the boldest shift toward renewable energies in the wake of the oil price shocks of the 1970s was to be made in Sweden: By 2015 the country was to derive half of its energy from tree plantations that were to cover 6–7% of the country's large territory (Johansson & Steen, 1978). Moreover, the country's

Figure 4.6 In 1976 Lovins forecast a 33% share of renewable energies in the U.S. primary energy supply: The actual share of 7.2% was composed mostly of water power and wood, with the new renewable (wind, solar, geothermal) providing only 0.42% of the total. Based on Lovins (1976) and data in EIA (2009).



reedlands were to become an important source of pelleted phytomass (Björk & Granéli, 1978). Those visions fell apart as rapidly as their U.S. counterparts, but a large-scale Swedish quest for biomass energy was reincarnated during the 1990s in the form of new plans for massive willow (*Salix viminalis*) plantations to be harvested four to six years after planting and then in three to four year intervals for at least another 20 years (Helby, Rosenqvist, & Roos, 2006). The principal use of the wood was to be combustion for district heating and in combined heat and power generation plants.

New operations received government subsidies of 10,000 SEK/ha at planting and in 1998 the Swedish Environmental Protection Agency envisaged more than 100,000 ha of energy willows in production by 2005 and nearly 400,000 ha by 2020. Here are the prosaic realities of 2009. Sweden has no large-scale cultivation of reeds for energy and no mass-production of pelletized reed phytomass. There has been a massive retreat from willow plantings: After a linear ascent to about 14,000 ha between 1989 and 1996 the further expansion of willow plantings had stopped—leaving the area at about 10% of the extent where it should have been by now—and some 40% of farmers have either retreated from willow cultivation or are regretting that they ever turned to that kind of silviculture.

And the country's energy balances show that in 2008 all combustible renewable and wastes (dominated by wood) supplied less than 2% of all primary energy. And so it appears that this attempt to energize a modern society by coppiced willows (an image that invokes medieval landscapes of severely pruned trees) is not turning into a harbinger of things to come.

Given this history it is only fair to ask: Are today's forecasts of anticipated, planned, or mandated shares of renewable energies as unrealistic as those of three decades ago? Jefferson (2008, p. 4116) gave a reasoned answer that covers all the major points: "Targets are usually too short term and clearly unrealistic . . . subsidy systems often promote renewable energy schemes that are misdirected and buoyed up by grossly exaggerated claims. One or two mature energy technologies are pushed nationally with insufficient regard for their costs, contribution to electricity generation, transportation fuels' needs, or carbon emission avoidance."

I will illustrate these general observations by a number of prominent examples. Two of the eight countries whose energy transitions were traced in this book's previous chapter—oil-rich Saudi Arabia and hydrocarbon- and coal-rich Russia—have no (formal or informal) goals for using more renewable energy for domestic consumption. There is an academic project of renewable scenarios for Saudi Arabia (Al-Saleh, Upham, & Malik, 2008)—but the country's oil minister warns against any rapid shift to renewables (because it may result in energy shortages once the global economy recovers) even as he expresses his hope that Saudi Arabia will become "the world's largest exporter of clean electric energy produced from our abundant sunlight"—but not for another 30 to 50 years (Patel, 2009).

In contrast, Europe is the leader of renewable promises. The EU's *Second Strategic Energy Review* set "the ambitious objective of raising the share of renewable energy sources in its final energy consumption from around 8.5% in 2005 to 20% in 2020" as "a necessary contribution to the fight against climate change and the effort to diversify our energy mix" (CEC, 2008, p. 20). Because most of today's renewable share consists of hydroelectricity, those member countries with minimal water power will find that target extremely challenging as they would have to add new renewable capacities only in wind and solar electricity generation and in biofuels. But if the biofuel target will also include all aviation fuel, then it will be challenging for every EU state: The vision of every fifth jetliner powered by bio-kerosene by 2020 is surely a heady one! No matter, "green" activists are urging to aim far higher: For example, a report prepared by Friends of the Earth Scotland and WWF Scotland concluded that renewables (hydro, wind, waves, and geothermal) can supply 60% of the Scotland's electricity by 2020 and 143% of the demand by 2030 (FOE Scotland, 2009).

Sweden is at it again, and in an official manner: In June 2006 the governmental Commission on Oil Independence issued its report boldly entitled *Making Sweden an OIL-FREE Society* (COI, 2006). That would be a stunning accomplishment, particularly as it is to be done without any reliance on nuclear generation (the existing plants are to be closed). Achieving that goal would take more than rejuvenating the moribund willow plantings, the Swedes would also have to give up all flights to Thailand, and refuse to eat Spanish produce: I would rate the likelihood of reaching the goal at less than 0.3%, a 3σ event. But reading beyond the report's catchy title reveals more realistic goals, beginning with a 20% increase in overall efficiency of energy use, and reducing gasoline and diesel use in transportation by 40–50% and cutting the use of refined fuels in industry by 25–40%. "Oil-free" would apply only to heating residential and commercial buildings: "by 2020 in principle no oil should be used" by those sectors, with biofuels and renewable electricity filling the need.

Japan, not too long ago considered as a leader in solar heat and PV conversions, has only a minimalist renewable energy target of 1.6% of the total supply by 2014 compared to 1.3% in 2009. In contrast, China, now the world's largest user of coal and the leading emitter of CO_2, has set a very ambitious target of 15% of all primary energy supply coming from renewables by 2020, but some Chinese policymakers believe that with the accelerated development of wind and solar generation the actual share will be at least 18% and perhaps even 20%, matching the EU goal (*China Daily*, 2009). I would classify the probability of meeting the last target as another notable 3σ event.

But, and despite the country's weakening economic and strategic power, it will be the U.S. achievements that will prove or disprove the possibilities of an accelerated shift toward renewable conversions. Although the country has no formal government-mandated target for future renewable energy shares, it has no shortage of goals and proposals. The Utility Solar Assessment Study offered what it called "a comprehensive roadmap for utilities, solar companies, and regulators" to produce 10% of U.S. electricity by PV generation by 2025, a goal predicated on costs below $3 per peak watt by 2018 and by substantial grid expansion (USA, 2008).

Because wind-powered electricity generation is technically the most mature choice it is hardly surprising that most specific production targets refer to its future shares of electricity generation. The U.S. Department of Energy projected 20% of U.S. electricity generated by wind turbines by 2030, a goal requiring about 250 GW of new capacity on land and roughly 55 GW offshore (USDOE, 2008). For comparison, the European Wind Energy Technology Platform, launched in 2006, is relatively slightly more ambitious, calling for 180 GW (including 40 GW offshore) by 2020 and 300 GW (half offshore), or about 25% of the EU's electricity consumption, by 2030 (TPWind, 2008). But by far the most ambitious energy transition challenge for the United States was presented by the country's former vice president.

Gore's fundamental premise is that the country's three major challenges—the economic, environmental, and national security crisis—had a common denominator in "our dangerous over-reliance on carbon-based fuels." And Gore is confident that he has an effective solution (Gore, 2008, p. 4):

> But if we grab hold of that common thread and pull it hard, all of these complex problems begin to unravel and we will find that we're holding the answer to all of them right in our hand. The answer is to end our reliance on carbon-based fuels . . . We have such fuels. Scientists have confirmed that enough solar energy falls on the surface of the earth every 40 minutes to meet 100 percent of the entire world's energy needs for a full year. Tapping just a small portion of this solar energy could provide all of the electricity America uses. And enough wind power blows through the Midwest corridor every day to also meet 100 percent of US electricity demand. Geothermal energy, similarly, is capable of providing enormous supplies of electricity for America. The quickest, cheapest and best way to start using all this renewable energy is in the production of electricity. In fact, we can start right now using solar power, wind power and geothermal power to make electricity for our homes and businesses.

Gore's bold goal called for "a strategic initiative designed to free us from the crises that are holding us down and to regain control of our own destiny": He challenged the nation "to commit to producing 100 percent of our electricity from renewable energy and truly clean carbon-free sources within 10 years" and he thought that goal to be challenging but "achievable, affordable and transformative." His confidence was based on his expectation that "as the demand for renewable energy grows, the costs will continue to fall" and then he used the silicon analogy to explain the anticipated cost declines. I have already explained the completely misleading and entirely inappropriate choice of this analogy in the preceding section.

Here I will focus on another critical matter, on Gore's unrealistic appraisal of technical and infrastructural possibilities. In 2008 the United States generated about 4 PWh of electricity with almost exactly one half coming from coal-fired stations, 20% from nuclear fission, only a bit over 6% from hydro stations, and just 2.3% came from "new" renewables, that is, wind, geothermal, and solar (EIA, 2009). Because Gore wants to eliminate carbon-based electricity this would mean replacing 71% of the current generation originating in the combustion of fossil fuels. But if the country were to end up only with "renewable" means of electricity generation then the repowering should also affect the nuclear stations, whose operation emits no carbon but whose source of energy (fissionable isotopes) is obviously not renewable: Then the country would have to replace just over 90% of its current generation.

In 2007 the net summer capacity of the U.S. fossil-fueled stations was about 740 GW and they generated 2.88 PWh of electricity, which means that the load factor (number of hours they were generating in a year) was about 44% (with averages of 73% for base-load coal-fired stations but only 25% for predominantly peak-load natural gas-fired generation). In 2007 wind and solar electricity contributed just 35 TWh (less than 0.9% of the total), and with installed capacity of 17 GW its load factor was just 23%. This means (assuming a high degree of HV interconnections to distribute the concentrated wind generation) that two units of generating capacity in wind and solar would be needed to replace one unit of capacity currently installed in coal- and gas-fired plants—and the country would have to build about 1,480 GW of new wind and solar capacity in a single decade, or roughly 1.65 times as much as it had added between 1950 and 2007!

Annual capacity additions would have to average nearly 150 GW or, if they would start lower and then accelerate, they would have to reach more than 200 or 250 GW during the decade's last few years: This compares to the average net additions of less than 15 GW/year of all generating capacity during the two decades between 1987 and 2007, and to the record wind capacity addition of 8.5 GW in 2008 (AWEA, 2009). These contrasts alone—most notably the fact that annual additions would have to average 20 times as much as the record 2008 rate—should suffice to demonstrate the impossibility of the task. Moreover, that impossible feat would also require writing off in a decade the entire fossil-fueled electricity generation industry and the associated production and transportation infrastructure, an enterprise whose replacement value is at least $2 trillion—while concurrently spending no less than $2.5 trillion (assuming, conservatively, $1,500/kW) to build the new renewable generation capacity.

But those new capacities would be concentrated in the Great Plains (with wind power densities being the highest in their northern part) and in the Southwest (with southern California, Nevada, Arizona, and New Mexico having the highest average insolation), and these regions have currently either only weak connections with the rest of the country or, for the most part, no major HV transmission links to major load centers on the East and West Coast at all. Repowering of the United States would thus have to be preceded by considerable rewiring, by creation of new, high-capacity, long-distance transmission links. This limited transmission capacity to move electricity from the new power centers in the Southwest, Texas (Texas has its own grid weakly connected to the rest of the country), and the Midwest has been already delaying new wind projects even as wind generates less than 2% of all U.S. electricity. The United States now has about 265,000 km of HV lines, and at least 65,000 km of new high-capacity lines would be needed to rewire the nation, at an aggregate cost surpassing $100 billion.

Once again, this is a very conservative estimate (assuming about $2 million/km), as the costs are bound to escalate. A key factor in this matter, besides the usual uncertainties concerning future inflation rate and rises in the cost of materials, is a lengthy regulatory approval process that takes many years even before a new line construction can begin. Installing in 10 years wind- and solar-generating capacity more than twice as large as that of all fossil-fueled stations operating today while concurrently incurring write-off and building costs on the order of $4–5 trillion and reducing regulatory approval of generation and transmission megaprojects from many years to mere months would be neither achievable nor affordable at the best of times: At a time when the nation has been adding to its massive national debt at a rate approaching $2 trillion a year, it is nothing but a grand delusion (to say nothing of the fact that solar generation is far from ready to be deployed on a GW scale).

Gore's repowering plan was actually preceded by a more modest, but still very ambitious, plan advanced during the summer of 2008 by T. Boone Pickens, a Texas oilman, billionaire, and former corporate raider. His 10-year energy plan for United States had what I called an appealing "cascading simplicity" (Smil, 2008). Pickens wanted to fill the Great Plains ("the Saudi Arabia of wind power") with wind turbines; this new wind power would replace all the electricity currently produced by burning natural gas. This natural gas freed by wind-powered generation would be used to run efficient and clean natural gas vehicles. And this substitution would create new, massive, domestic aerospace-like industry (providing good jobs and bringing economic revival to the depopulating Great Plains) while cutting U.S. oil imports by more than one third and helping to put the country on a better fiscal foundation.

Pickens outlined the plan to the Congress and promoted it with a $58 million advertising blitz to rally public support (www.pickensplan.com). There is no arguing about the key reason behind the plan: Pickens rightly saw the U.S. addiction to oil, especially with the high prices of the summer 2008, as a threat to "our economy, our environment and our national security" that "ties our hands as a nation and a people." But his plan would require building more than 100,000 wind turbines, connecting them to large cities with at least 65,000 km of transmission lines, and converting tens of millions of cars to natural gas fuel, a daunting task for a single decade. The plan proposed roughly $1 trillion in private investment to build the large wind farms and (conservatively estimated) another $200 billion in order to construct the requisite high-voltage transmission lines that would connect those giant wind farms to densely populated coastal regions.

Al Gore has not withdrawn or substantially modified his plan and his organization (wecansolveit.org) went on to publish pathetic prayer-like advertisements imploring "our leaders" to "free us from our addiction to oil . . . Save us from this climate crisis . . . Give us 100% clean electricity within 10 years." Pickens first acknowledged that his grandiose plan has little chance to be realized anytime soon due to inadequate transmission links, late in 2008 he switched his vehicular gas proposal from passenger cars to trucks (because only about 1% of America's filling stations are equipped to sell compressed natural gas), and by July 2009 the economic downturn led him to delay it: "I didn't cancel it. Financing is tough right now and so it's going to be delayed a year or two" (Rascoe & O'Grady, 2009, p. 1). Even his own project, that was planned to be the world's largest, 4-GW wind farm near Pampa in Texas, was set aside because the $4.9 billion worth of the needed transmission lines will not pass all regulatory requirements before 2013.

The Grand Energy Transition (GET) plan proposed by Robert Hefner, a lifelong natural gas explorer and producer, amounts basically to the second part of the Pickens Plan, but with some other questionable provisos (Hefner, 2009).

Hefner believes not only that U.S., and global, natural gas resources are larger than those of crude oil (a view shared by others) but that U.S. attainable gas reserves are as large or perhaps even larger than the country's remaining minable coal deposits. Although the last claim may be too optimistic, the latest assessment by the Potential Gas Committee (2009) boosted the estimate of the U.S. gas resources by 39% compared to the 2006 total.

In any case, Hefner's plan calls for retrofitting and converting half of the U.S. vehicle fleet to natural gas by the year 2020. He also believes that this would not be a difficult conversion because a natural gas grid already extends to most of today's urban gasoline filling stations as well as to some 63 million homes where more than 130 million vehicles could be filled with a convenient home-fueling appliance. According to Hefner this conversion would cut the oil imports by about 250 Mt/year (in 2008 the country imported nearly 640 Mt), save trillions of dollars of foreign payments, trigger some $100 billion of private investment due to higher natural gas demand, and add some 100,000 new jobs. Actually the most important part of the GET plan that would unleash these massive changes is the elimination of taxes on labor and capital and their replacement with a "green" consumption tax to be levied initially on coal and oil products. Even if gas resources were superabundant, an obvious question to ask concerns the likelihood of the U.S. Congress acting to eliminate all taxes on labor and capital.

I will note just one more of several recently issued sweeping proposals for reducing U.S. dependence on fossil fuels, Google's plan to repower the United States that was released in October 2008, shortly after Gore's challenge. Google's *Clean Energy 2030* called for "weaning the U.S. off of coal and oil for electricity generation by 2030 (with some remaining use of natural gas as well as nuclear), and cutting oil use for cars by 44%" (Google, 2008). This rapid energy transition rests on three key steps. First, cutting the fossil fuel–based electricity generation by 88%. Second, deploying aggressive end-use electrical energy efficiency in order to cut the anticipated 2030 demand by 33% and hence keep the overall demand flat at the 2008 level. And, finally, by raising the sales of plug-in vehicles (hybrids and pure electrics) to 90% of all new car sales by 2030 and boosting the conventional vehicle efficiency to 45 mpg by 2030.

Based on the past experience and on the current baselines I conclude that keeping the nationwide electricity demand flat at the 2008 level by 2030 and raising the average car performance to 45 mpg are technically eminently doable goals. Having plug-in vehicles taking over in just two decades is an entirely different challenge, and eliminating nearly 90% of all fossil-fueled electricity generation is a goal whose achievement is based on some unrealistic assumptions. The Google plan proposes to do that by eliminating all electricity produced by burning coal and liquid fuels and about half of all electricity originating in gas-fired stations: Their generation amounted to about 2.5 PWh in 2007 and they are to be replaced by 380 GW of new wind, 250 GW of new solar, and 80 GW of new geothermal capacity.

Google's plan points out (correctly) that such rapid build-ups of electricity-generating capacity are not without precedent: Most notably, more than 200 GW of natural gas-fired capacity were added between 1998 and 2006, including 60 GW in a single year (in 2002); and during the 15-year period between 1972 and 1987 more than 85 GW of new nuclear generation capacity were put in place (with peak addition of almost 10 GW/year) raising the share of nuclear electricity generation from about 3% to 18%. Unfortunately, both comparisons are categorical errors, and the second one should not be invoked to demonstrate possibilities of rapid capacity growth because the history of U.S. nuclear expansion is actually the best possible example of perils inherent in forecasting the transition toward new energy conversions.

In 2008 the average capacity of newly installed U.S. wind turbines was about 1.7 MW, with the largest units between 3 and 5 MW, and today's large-scale industrial-size PV units remain below 1 MW—while gas turbines larger than 100 MW have been available since 1976, units around 200 MW are common and in 2008 Siemens completed the world's largest gas turbine, rated at 340 MW (Siemens, 2009). Moreover, it is usually quite easy to accommodate those units at the existing power plant sites (they need very little space) and they can be ready to generate in a few months; indeed, some gas turbines, such as P&W's SwiftPac available in 30-MW and 60-MW sizes, can be ordered fully assembled and packaged in multi-trailer modules and are able to generate electricity in less than a month after arriving at their location (Figure 4.7).

Figure 4.7 Pratt & Whitney's SwiftPac series of gas turbines (30–60 MW) used to generate electricity requires less than a month to install. Copyright (C) 2008 United Technologies Corporation. All rights reserved.

And turbogenerators in nuclear stations were added in unit capacities ranging from 300 MW to more than 1 GW!

In contrast, before large wind farms are assembled from hundreds of massive units their siting is subject to lengthy selection, environmental assessment, and approval process, and their completion (as Pickens so quickly discovered) *must be preceded* by the construction of requisite high-voltage transmission lines, a process that demands even lengthier route selection and regulatory approval. No less importantly, in order to generate 2.5 PWh of electricity, Google's renewable conversions would have to achieve average load factors of 35% for both wind and solar and 80% for geothermal generation. The last rate is realistic, the first two are impossibly high as national means rather than as exceptional ratings.

Years of experience with European wind power give a clear long-term answer: Average load factor for the European Union between 2003 and 2007 was just 20.8%, with the high of 29.3% for Ireland and Greece and the low of 18.3% for Denmark (Boccard, 2009). Similarly, solar PV capacity factors average below 25% even in such sunny places as Arizona, and studies show that (because of the limited flexibility of base-load units) increasingly large amounts of unusable PV generation would be produced when PV capacities would reach 10–20% of a system's total capability (Denholm & Margolis, 2007). And, to mention only one additional notable complication, the single largest item in Google's appraisal of net savings accruing from this rapid forced transition are carbon credits for CO_2 not emitted, rated initially at \$20/ton of CO_2 and doubling by 2030—but no such mechanism is in place and nobody knows when, indeed even if, it will be enacted by the Congress.

Uncertainty regarding this key profit-making assumption underscores a major failing of all of explicit transition plans or bold aspirations: Their goals might have a fair probability of success only if a concatenation of extraordinarily advantageous circumstances and radical departures from prevailing modes of action (most often a strong government intervention) and resource valuation (be it the proposed carbon credits or life cycle assessment pricing) takes place. But the history of energy transitions makes it clear that many unexpected discontinuities have strongly affected the economic viability, public acceptance, and governmental support of new fuels and new conversion techniques and that they had changed, or even reversed, their adoption or diffusion rates.

The most prominent examples of this kind that have been encountered in the past three decades are listed here in order that does not imply any ranking: unpredictable shifts in energy prices; relatively sudden arrival of major new consumers to the global market; loss of faith in approaches that were initially touted as effective and rewarding solutions, a process that begins with a sudden embrace and ends with an equally sudden abandonment of problematic or immature techniques; effects of long-term environmental implications of energy use; unprecedented economic crises; fiscal mismanagement whose painful effects can be postponed but not averted; and recurrent eagerness of governments to support fashionable solutions whose long-term impact turns out to be limited or nonexistent.

Here are some essential expansions of these seven prominent examples. Unprecedented rise of world crude oil prices between 1973 and 1981 (from around $2/bbl to as high as $38/bbl in monies of the day) followed by their precipitous fall (monthly mean as low as $11/bbl in July 1986) were the main reasons for the fact that the 1979 peak level of global oil consumption was not surpassed until 1994, and that the new exploratory drilling, overall investment in the sector and new oil discoveries entered a long period of post-1985 slump, and that the oil stocks were the least profitable stock market play of the entire 1990s.

As for the arrival of new major and rapidly growing consumers of energy whose entry into the global market for fuels has had a strong effect on prices, China is the top example, with India a distant second. Who would have said in 1980, four years after Mao's death, or in 1990, a year after the Tian'anmen killings when China continued to be a significant oil exporter with a relatively limited manufacturing base, that at the beginning of a new century the country will become a major oil importer, a veritable factory for the world, the planet's second-largest energy user and the first emitter of greenhouse gases? Looking ahead, India (whose population will surpass that of China in about three decades) has a no smaller potential to alter the global energy market, especially given the fact that its per capita consumption of primary energy is still so much lower than in China (in 2010 just short of 20 GJ/capita in India vs. nearly 65 GJ/capita in China).

Nuclear electricity generation is not the only prominent example of a rather sudden loss of faith in a new technique that was seen, for years or even decades, to offer an ultimate (or nearly so) solution before its sudden retreat. At the height of the second oil price crisis in the late 1970s it was the oil production from shales that was to save the United States, and that was supported by a huge commitment of federal monies: the Energy Security Act of 1980 budgeted $17 billion (with a further $68 billion to follow) in order to set a massive new industry producing two million barrels of oil from the Rocky Mountain shales by 1992, but the projected fizzled out rapidly and was completely abandoned in 1985 after the oil prices collapsed.

Two decades later we were assured that within 10 years fuel cells will be the standard energizers of our road vehicles. Market value of Ballard Power Systems of Burnaby, BC, a principal developer of hydrogen-powered fuel cells, topped C$300/share in early 2000—but by the end of 2008 it stood at C$3/share and the company had abandoned any further development of hydrogen-fueled propulsion and survives by selling fuel cells for forklifts and stationary units used for backup electricity generation.

In 1980 acid deposition (a problem largely eliminated by the combination of flue gas desulfurization and switch to low-sulfur fuels, above all to natural gas) was the dominant environmental worry for the Western energy industries.

That concern hardly registers now, with the worries about global warming dwarfing all other environmental impacts of modern energy use.

Little has to be said about the impact of sudden, massive (indeed global) economic dislocations. The global economic downturn that began in 2008 has been, undoubtedly, the worst event of its kind since World War II and the ensuing drop in demand, sharply declined availability of credit, and enormous deficit spending on assorted bailout plans has made many energy targets excessively ambitious. Moreover, nobody knows how deep and how protracted its eventual impact will be. Fiscal mismanagement whose extent and depth eventually comes to limit the actions governments and consumers can make is frighteningly illustrated by the state of U.S. finances, with a grand total of debts (including uncovered future federal and state obligations) now surpassing $60 trillion, roughly five times the country's annual GDP. And the ways in which governments subsidize energy industries and new conversions have ranged from unjustifiable persistence (with tens of billions poured into fusion research during the past 50 years and with nuclear research receiving more monies than all other forms of energy combined) to unpredictable fickleness (credits for wind-powered generation).

The abrupt cessation of U.S. nuclear expansion is perhaps the best illustration of how exaggerated aspirations can end in outcomes that are a fraction of original goals (Smil, 2003). Expectations during the early 1970s were for annual capacity additions exceeding 50 GW in light water reactors beginning during the mid-1980s; at that time the first liquid metal fast breeder reactors (LMFBR) were to make their commercial entry and by 1995 they, too, were expected to add 50 GW/year of new capacity, a combination that was to eliminate all fossil-fueled electricity generation before 1990. In reality, no new nuclear stations were ordered in the United States after 1978 and there is not a single operational LMFBR.

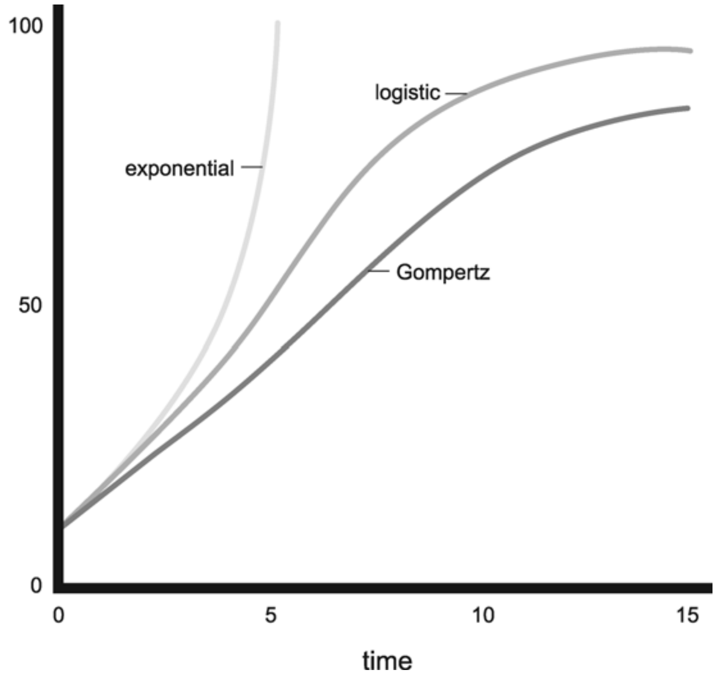
Given all of these uncertainties it is not surprising that the past performance of renewable conversions cannot be used to prime quantitative models of their future advances. The key problem with this approach is that there is not a single growth curve to follow. Growth and diffusion of most phenomena—including energy resource substitutions and adoption of new fuel and electricity conversion techniques—is a process that almost inevitably follows a progression that is distinguished with its slow initial advances followed by a rapid rise, an eventual inflection point, and rapidly declining increments towards saturation. However, when complete or nearly complete substitution or diffusion processes are studied retroactively, some of them are found to conform to a logistic equation while others are best fitted with its variants including, most notably, Gompertz, Weibull, and hyperlogistic distribution (Banks, 1994).

Kramer and Haigh (2009) tried to translate this well-known progression into what they called "the laws of energy-technology deployment." The first law dictates a few decades of exponential growth for new conversions (amounting to an order of magnitude increase in a decade), the second one describes linear gains after reaching "materiality," that is around 1% of world energy mix. This is nothing else but an alternative description of a ubiquitous growth process—but, as always, the specifics will vary, and saying that the deployment curves of different innovations are remarkably similar is correct only in the sense that the progress must resemble a variant of a growth curve.

Actual growth pattern of any particular innovation cannot be selected *a priori* with a high degree of confidence and the best fit (with some inevitable scatter) can be accurately ascertained only *ex post*. For example, a forecast based on a logistic curve rather than on a Gompertz distribution would end with the same outcome but the former trajectory has a much stronger (nearly exponential) initial growth phase and a much higher inflection point than the latter, but choosing the former on the basis of an early steep growth may turn out to be a major error due to common delays and disruptions of those growth processes that are subject to vagaries of public acceptance and that depend on continuous high flow of governmental subsidies or private investment (Figure 4.8).

A sudden end of the United States' first exponential wind power growth of the 1980s is an excellent example. Between 1980 and 1986 the installed capacity grew at an annual rate of 84%, rising from just 8 MW to 1.265 GW; even if the subsequent growth rate would have been halved, the total capacity would have

Figure 4.8 Comparison of logistic, Gompertz, and exponential growth curves.



reached about 84 GW by 1996, or about 66 times the 1986 total—but in reality (once the subsidies stopped) the annual growth rate fell to just 2.3% and the 1996 total was just 1.614 GW, less than 30% above the 1986 level. Consequently, we have to wait until after most of the growth or adoption process will have been completed before we can get on a firmer quantitative forecasting ground—and given the fact that most new renewable energy conversions have, so far, claimed only very small fractions of their respective markets (wind in several EU countries being the most notable exception), we cannot deploy any particular distribution in confident forecasting.

But some things we can affirm with a great deal of confidence. Even if the boldest national goals for a relatively rapid transition to the new renewables were met, the global primary energy supply in 2025 or 2030 will be still overwhelmingly dominated by fossil fuels and it is highly unlikely that the combined share of coals and hydrocarbons will fall below 50% of the aggregate energy demand by 2050. A world without fossil fuel combustion may be highly desirable, and eventually it will be inevitable, and our collective determination could accelerate its arrival—but making it a reality will demand great determination, extraordinary commitment, substantial expense, and uncommon patience as the process of a new epochal energy transition unfolds across decades.

CAUTIOUS ANTICIPATIONS: TRENDS AND POSSIBILITIES

This book had several independent goals. In its first chapter I wanted to make sure that a reader (and particularly anybody whose interest in energy matters has come about because of the recent preoccupation with such concerns as the end of oil or catastrophic global warming) appreciates the basic properties and complexities of modern energy systems, their major resources, conversions, uses, infrastructures, and impacts. This is important because, contrary to a standard view that reduces the process of energy transitions to changes of fuel base (oil replacing coal) or shifts in generating electricity (wind power replacing electricity produced by burning coal), those components, fundamental as they are, form only a partially predictable dynamic whole and all of them keep changing, some fairly rapidly while others display relatively long periods of surprising inertia. As a result, some of the long-established, gradually progressing energy transitions will continue even as the composition of primary energy supply changes.

Secular gains in energy efficiency—expressed most generally as the declining energy intensity of national economies (with less energy needed per unit of GDP) and evident in sectoral improvements (most notably in lower energy use in industrial production and transport) and in less wasteful performance of all major converters (be they fridges or jet engines)—will continue and, given the still ubiquitous opportunities for further improvements, the pace of their advances should not be any slower during the coming two or three decades than it has been during the past generation. For example, a detailed assessment of U.S. energy use estimated that improved efficiency could cut the country's overall energy use 23% by the year 2020 (Granade et al., 2009). The only major uncertainty regards the household energy use in high-income countries, which has been up since 1990 not only in North America but also in Japan and in the European Union where it rose by more than 10% (EEA, 2008): Will it finally stabilize and begin to decline?

There are three major reasons why the gradual trend of global energy supply decarbonization should actually accelerate: Larger volumes of natural gas are becoming available due to increased global LNG trade; technical advances in extracting U.S. shale gas has led to a substantial upward revision of the country's natural gas reserves and this will lead to the fuel's wider use; and new wind-driven and PV electricity generation will have no direct carbon emissions. The third long-term energy transition that will continue its progress is the rising share of electricity in the final energy supply, and if many national goals for relatively high shares of electricity from new renewable conversions are met, or approached, it should also accelerate.

The second chapter offered a truly long-term historical perspective by surveying the grand energy transitions from biomass to fossil fuels and from animate power to mechanical prime movers and the rise of electricity, the most flexible form of all energies. Availability of reasonably good statistics of global energy use augmented by serviceable estimates of preindustrial performance made it possible to conclude the chapter with revealing quantifications of these long-term shifts in resources and prime movers. The record on the global scale is unequivocal: All of the past shifts to new sources of primary energy have been gradual, prolonged affairs, with new sources taking decades from the beginning of production to become more than insignificant contributors, and then another two to three decades before capturing a quarter or a third of their respective markets.

And the record is also unequivocal as far as the notion of any mechanistically preordained primary energy transitions is concerned: As in so many other cases, complex and nuanced reality does not fit any simplistic deterministic models that are supposed to capture the past and reveal the future. Because of the capital mobilization and technical advances required for any large-scale resource extraction and conversion, and because of extensive infrastructures needed to bring the modern energies to their global markets, it is inevitable that primary energy transitions must have a number of generic, underlying properties that constrain the rise of individual fuels or modes of electricity generation, the pace of their maturation, and their eventual retreat. But these broad commonalities leave a great deal of room for exceptions and departures from generally expected norms, and unpredictable changes of the overall economic, social, and political environment can affect even what appeared to be the strongest trends.

The gradual nature of energy transitions can be also traced on the global scale as far as the two important ways of primary electricity generation, water and nuclear power, are concerned. And, again, the development of both of these resources offers excellent illustrations of unpredictable shifts. Who would have said in the mid-1970s, the peak decade of worldwide dam construction, that 20 years later people would be asking if there is such a thing as a good dam and the World Bank would be reluctant to lend money for new hydro projects in low-income countries? And there was also nobody who predicted that in less than two decades that nuclear generation—in 1965 a highly promising technique on the verge of large-scale expansion and one expected to take over most, if not all, electricity generation by the century's end—would come to be seen, at best, as a dubious proposition, at worst as a regrettable past error and completely undesirable future choice.

And surveying the rise of the currently dominant prime movers reveals, yet again, incremental ascents with decades elapsing between the first technical breakthroughs and the conquest of significant shares of respective markets. In addition, the record of modern prime mover development suggests a remarkably high degree of persistence as the machines that have been with us for more than 100 years (gasoline- and diesel-fueled internal combustion engines, steam turbines, electric motors) or for three generations (gas turbines) not only continue the dominance of their respective niches but do not appear to be threatened by any new techniques promising their rapid displacement.

The third chapter focused on eight specific national examples of long-term energy transitions that were selected on the basis of historical importance, overall representativeness or, for the very opposite reason, because they illustrate notable idiosyncrasies of some substitution processes. To say that at a national level anything is possible would be an impermissible exaggeration, but the record displays a remarkable scope of developments, ranging from the centuries-long dominance of English coal to an almost instant demise of the Dutch coal mining, from a highly idiosyncratic and swiftly changing evolution of Japan's energy use to the U.S. orderly sequence of fuels during the first half of the twentieth century followed by a surprising post-1960 near-stasis of the primary energy make-up.

These national examinations offer a few obvious lessons. Small, resource-rich, or affluent, countries can do what large, resource-poor and low-income nations cannot replicate (Dutch and Kuwaiti experience holds no lessons for India and Ethiopia). National commitment to a large-scale technical transformation can make a real difference (French nuclear power is perhaps the best testimony to that). Coal, particularly as the fuel for base-load electricity generation, has shown not only a remarkable staying power but, in Asia, also a phenomenal resurgence (China's and India's rising extraction, Indonesia's growing exports). Refined liquid fuels that are used to energize all modern transportation (electric trains being the only notable exception) cannot be easily and rapidly replaced by alternatives. At the same time, these resource-specific lessons may have little or no relevance for the coming transition to a non-fossil energy system.

In the first three sections of this closing chapter I have addressed the recent expectations concerning the unfolding transition from the combustion of fossil fuels to the harnessing of a variety of renewable energies. In order to map out the possibilities and limits of this complex process I had first assessed the potential contributions of all major renewable resources and the status of their commercial or experimental conversions and then I took a closer look at some key factors that will influence the pace of the coming transitions and, finally, I gave some notable examples of actual national energy transition targets and briefly deconstructed a few plans that presented the boldest scenarios for the new epochal shift from fossil to renewable energies.

Among the new renewable conversions, wind-powered electricity generation stands out due to its recent rapid technical maturation, declining cost and rising unit capacities (MW-sized turbines), annual additions (GW-sized), and overall system capabilities (tens of GW in several countries). Wind-powered electricity generation is thus at the forefront of the unfolding energy transition and there is no doubt that countries with particularly windy climates can generate not just 20% but 30% of their electricity using large wind turbines (Zubi, Bernal-Augustín, & Marín, 2009)—particularly if they are relatively small and are already well connected to grids of adequate capacity or if the construction of new links precedes the commitment to higher rates of wind-driven generation. Denmark—where wind generated almost 20% of all electricity in 2007 and where large offshore projects are to raise the share to 50% by 2025—is a foremost example of this combination: It has a relatively small market (total generating capacity is less than 10 GW) and excellent interconnections with the hydro-rich Scandinavia to the north and with large thermal systems in Germany and beyond to the south.

But the challenge is different in large countries whose wind resources are concentrated far from major load centers (North Dakota is 2,600 km from New York, in European terms more than the distance between Paris and Moscow) and where extensive, and expensive, up-front investment in new high-voltage transmission links will be needed if the shares of wind electricity are to surpass 15% or 20%. Load factors will have to get better than the recent worldwide mean of only about 20% and typical national means of less than 25%—but the best way to raise them, by setting up large wind farms offshore, has its own problems, ranging from high construction costs to increased maintenance and lower durability of components set in extreme environments.

There can be no long-term future for renewable electricity without a mass-scale commercial success of PV generation, but despite some remarkable progress in lowering the cost of producing and installing the PV modules and increasing their maximum unit capacities, this conversion is considerably less mature than the harnessing of wind power: In 2007 the world added about 94 GW of wind turbines but only about 4 GW of peak PV power. Solar enthusiasts will say otherwise (and have been saying so for many years), but I would argue that it is not at all certain if we are just years from the formation of a

J-bend on the technique's growth/adoption logistic curve—or if that take-off point is far from being so imminent. Material and infrastructure constraints are even more important than for wind-driven generation. Rare metals (cadmium, gallium, selenium and tellurium) are required to make the cells, and even cost-competitive modules could not displace fossil-fueled electricity generation in less sunny climates without what are still only visionary mega-transmission links from the Algerian Sahara to Europe or from Arizona to the Atlantic coast.

And as with all technical innovations, a definite judgment regarding long-term capability and reliability of wind-driven or PV generation is still many years ahead. Decades of cumulative experience are needed to assess properly all of the risks and benefits entailed in large-scale operation of these new systems and to quantify satisfactorily their probabilities of catastrophic failures and their true lifetime costs. This means that we will be able to offer it only after very large numbers of large-capacity units will have accumulated at least two decades of operating experience in a wide variety of conditions. This ultimate test of long-term dependence and productivity will be particularly critical for massive offshore wind farms or for extensive PV fields in harsh desert environment.

Future levels of production and adoption of renewably produced fuels have no less uncertain prospects. The best Brazilian sugar cane–based practices aside, the current ways of relatively large-scale ethanol crop–based production cannot be—due to the combination of high energy costs, serious environmental impacts, and major effects on food prices—a basis for an industry producing liquid transportation fuels at scales that would cut the demand for refined fuels by substantial (at least 20–25%) shares. What has been achieved so far (ethanol and biodiesel) has come about as a result of very large and very questionable subsidies (Steenblik, 2007). And all of those repeatedly extolled options based on waste cellulosic substrates (crop and forest residues) or on large-scale cultivation of high-yielding species (switchgrass, miscanthus, jatropha) has yet to reach even the minimal threshold of large-scale commercial viability and hence they should not be seen as imminent and reliable providers of alternative fuels.

And in all cases the renewable energy enthusiasts do not sufficiently recognize the challenge of converting the existing (and basically a century old) system based on centralized extraction and conversion of energies with very high power densities to a system based on harnessing low power density flows to be used in relatively high power density urban areas. Decentralized energy provision, a holy grail of true green believers, is fine for a farmstead or a small town, not for the large cities that already house most of the world's humanity and even less so for megacities (such as today's Tokyo, Shanghai, or Mumbai) where most of the world's population will live by 2050.

An even greater (and curiously rarely noted) challenge will be the replacement of fossil fuels used as key industrial feedstocks. Unique properties of coke made from coal have made it the reduction agent of choice for smelting iron from ore. Charcoal is an excellent form of metallurgical carbon, but its fragility precludes its use in modern massive blast furnaces, and at the rate it would be needed for a complete replacement of coke in today's pig iron smelting (roughly 900 Mt/year, or about 3.5 Gt of dry wood), tree plantations for its production would take over some 350 Mha, an equivalent of almost two thirds of Brazil's forest—a most unlikely proposition. Nor do we have any plant-based substitutes for hydrocarbon feedstocks used in making plastics or synthesizing ammonia (production of fertilizer ammonia now needs more than 100 Gm^3 of natural gas a year).

Because I have always preferred unruly realities to neat simplifications I have always had my doubts about the efficacy of supposedly revelatory models and, as I have demonstrated, the record of past energy transitions justifies this skepticism. And the economics of the entire energy supply offers no firm guidance either. After more than a century of coal-fired electricity generation we have internalized some of its key externalities (from enhanced mining safety to flue gas desulfurization) but we still have not accounted for the long-term cost of its NO_x and above all CO_2 emissions. After more than half a century of living with nuclear power we still dispute its real cost (including the near-perpetual guardianship of long-lived wastes), and this uncertainty is a key reason why most of today's visions of non-fossil futures do not feature mass-scale nuclear generation.

Consequently, all cost comparison and all claims of imminent investment or price parities or advantages should not be mistaken for decisive guides. And the situation is, if anything, even shakier with the claims of future competitive costs of wind-generated or PV electricity, or capital estimates for future wave or ocean thermal energy conversion (OTEC) stations or algal megaflows: All those claims and counterclaims depend on concatenated assumptions whose true details are often impossible to ascertain, on uncertain choices of amortization periods and discount rates, and all of them are contaminated by (past, present, and tacitly expected) tax breaks, government subsidies, and simplistic, mechanistic assumptions regarding the future decline of unit costs. One might think that repeated cost overruns and chronically unmet forecasts of capital or operating costs should have had some effect, but they have done little to stop the recitals of new dubious numbers.

That a lengthy process of maturation, perfection, diffusion, and widespread commercial adoption of new renewable conversions will require government interventions is not at all surprising, as none of the other innovations in the recent history of energy advances has done without it. But the very necessity of such interventions—particularly if they were to become excessively concentrated in one or two areas, or if a panicky assessment were to lead to unusually large "crisis" investment—raises the obvious questions regarding the continuity of policies under different governments, resilience of official policies during the period of highly fluctuating or precipitously declining prices, and the capacity to sustain high levels of investment/subsidies/tax preferences during the period of severe and prolonged economic crises.

Historical record of major energy transitions is one of slowly unfolding incremental gains and regularities—as well as one of surprising accelerations, retreats, discontinuities, and periods of stasis. Undoubtedly, some of these lessons will be applicable to the unfolding energy transition to renewable energies; other new trends will be idiosyncratic, molded by new economic and strategic realities. Evidence of the past transitions would suggest that a shift away from fossil fuels has to be a generations-long process and that the inertia of existing massive and expensive energy infrastructures and prime movers and the time and capital investment needed for putting in place new converters and new networks make it inevitable that the primary energy supply of most modern nations will contain a significant component of fossil fuels for decades to come.

Moreover, inherent constraints and complications accompanying large-scale commercial harnessing of renewable energies would only tend to make this new epochal transition an even more challenging and very likely a much more protracted affair than is commonly assumed. Unfortunately, common expectations of energy futures—shared not only by poorly informed enthusiasts and careless politicians but, inexplicably, by too many uncritical professionals—have been, for decades, resembling more science fiction than unbiased engineering, economic, and environmental appraisals. The list of seriously espoused energy "solutions" has run from that ultimate *fata morgana* of nuclear fusion to an irrepressible (and always commencing in a decade or so) hydrogen economy, and its prominent entries have included everything from liquid metal fast breeder reactors to squeezing 5% of oil from the Rocky Mountain shales.

And so (yet again) *nihil novi sub sole*, as today's renewable list contains such "solutions" as mass deployment of bobbing wave converters in coastal waters, flexible PV films enveloping houses (and even people), enormous solar panels unfolded from satellites in stationary orbits, algae disgorging high-octane gasoline by hundreds of millions of liters a year, or (one of the latest favorites) ingenious harnessing of jet streams' ferocious winds 12 km above the ground (Archer & Caldeira, 2009; Vance, 2009). Those readers of this book who are no older than their early forties will have an excellent chance to see how many of these energy salvations will become commercial ubiquities by 2050.

As always, I will abstain from any long-term quantitative forecasts, but looking a generation or two ahead I can envisage circumstances whose concatenation could speed up, rather that retard, the unfolding energy transition. Undeniable acceleration of global warming attributable to carbon emissions would be a powerful impetus for a faster change, as would be chronically high prices of crude oil and hopeless instability in the Middle East. The epochal transition from biomass to fossil fuels has been the very essence of modernization: Ours is an overwhelmingly fossil-fueled society, our way of life has been largely created by the combustion of photosynthetically converted and fossilized sunlight—and there can be no doubt that the transition to fossil fuels, beset as it was with the miseries of industrialization and rapid urbanization, created a world where more people enjoy a higher quality of life than at any time in previous history.

This grand solar subsidy, this still-intensifying depletion of an energy stock whose beginnings go back hundreds of millions of years, cannot last, and the transition to a non-fossil future is an imperative process of self-preservation for modern high-energy civilization. While I am skeptical about many exaggerated, unwarranted claims regarding the pace and the near-term exploits of new renewable conversions, I remain hopeful in the long run. The first grand energy transition, the mastery of fire, has been one of the great accomplishments that set the hominins irretrievably apart from the rest of the mammalian kingdom. The second grand energy transition, from foraging to sedentary cropping and domestication of animals, gave us eventually high cultures and led to historical consciousness and, millennia later, to the doorstep of the modern world.

The third energy transition, from biomass fuels and animate power to fossil fuels and inanimate prime movers, had created the modern world and the first truly global civilization. The forthcoming fourth energy transition is both desirable (above all on environmental and strategic grounds) and inevitable—but neither its pace nor its compositional and operational details are yet clear. Trying to predict them would be like trying to predict specific energy conversions, particular prime movers and their performances, and typical sectoral consumption levels of the late twentieth century fossil-fueled society in 1900.

At that time all three major kinds of fossil fuels were being extracted by increasingly efficient methods, electricity generation was spreading light and mechanical power in large cities, and most major components of the modern energy system (including large mines, drilling rigs, refineries, pipelines, tankers, and power plants) were in place. But the industrial practices, household and transportation energy uses, and the behavior of the entire energy system in 1900 would have been poor predictors of future accomplishments: there was no gasoline and no mass ownership of cars, there was electricity but barely any household appliances, there was energy-intensive chemical industry but no synthesis of ammonia, now (when compared on a molar basis) the single most important synthetic product and a key reason why the planet can feed seven billion people. And, of course, there was no flight, no gas turbines, no nuclear generation, and not a single item of consumer electronics.

Trying to envisage in some detail the global energy system of 2100, or even that of 2050, is an exercise bound to mislead as the past record is of little help. Fear is always an option. Perelman, writing in 1981, at the end of OPEC's second wave of rapid oil price rise, when an early shift away from fossil fuels was widely expected, concluded that "the degree of social stress and conflict during the coming transition period has sufficiently great destructive potential to constitute a serious problem" and he saw such conflicts and disorders as imminent during "the perennial energy supply problems of the 1980s and 1990s" (Perelman, 1981, pp. 195, 197). But during those two decades energy supply was abundant and after 1985 prices were relatively low: As always, informed concerns are highly advisable, exaggerated fears are counterproductive.

And while we cannot outline complex outcomes of the unfolding transition, we can learn a great deal from the general features of process that got us through the past energy transitions. Inevitably, all past energy transitions have stimulated technical advances and provided unprecedented opportunities for our inventiveness. All of them posed, inevitably, enormous challenges for both producers and consumers of new forms of energy; all of them required the abandonment of old components, habits, and activities; all of them necessitated the rise of new infrastructures and reorganization of existing ways of production and transportation; all of them were costly and protracted; and all of them caused major socioeconomic dislocations.

All of them had also eventually created more productive and richer economies and improved the overall quality of life—and this experience should be eventually replicated by the coming energy transition. There has been a widespread agreement that the new transition must be accompanied, indeed made less taxing, by higher efficiency of energy use. No doubt, a more vigorous pursuit of higher energy efficiency for common converters should be an essential accompaniment of the unfolding energy transition, and it should consist of an organic mixture of adopting proven superior techniques and promoting bold innovations that would result in major efficiency gains throughout the economy. Fortunately, possibilities of such gains remain no less promising today than they appeared two generations ago: This energy transition toward more rational energy use can continue for decades to come.

But *better conversion efficiencies alone are not enough*, they will just keep confirming a lasting truth of Jevons's venerable paradox that "it is wholly a confusion of ideas to suppose that the economical use of fuel is equivalent to a diminished consumption. The very contrary is the truth" (Jevons, 1865, p. 140). The second precondition of a successful new transition in all affluent nations must be to *avoid consuming more energy more efficiently*, and this means that by far the most important step that those countries should take are gradual but *significant overall reductions of energy use*. High-income economies now account for less than 20% of humanity but they claim half of all commercial energy; the United States alone, with about 4.5% of all people, consumes just over 20% of the world's fossil fuels and primary electricity. In per capita terms Americans now consume more than twice as much energy as do the citizens of the largest European economies (Germany and France) or Japan (8.5 vs. about 4.2 toe per capita).

Adjustments for territorial and climatic differences reduce this large gap disparity but the disparity remains large, especially given the extent of U.S. deindustrialization compared to still vigorous energy-intensive manufacturing in Germany or Japan. What has the United States got in return? Its average quality of life (regardless if it is compared in per capita GDP, life expectancy, or happiness terms, or by using the UNDP's Human Development Index) is not double that of the European Union or Japan, and not a few socioeconomic indicators are actually lagging the EU's or Japan's means. Maintaining this exceptionally high energy consumption level in a global economy where modernizing nations, led by China and India, are trying to improve their quality of life by raising their still low energy use (averaging 1.6 toe in China and less than 0.5 toe in India) is both untenable and highly undesirable—while the goal of reduced energy use is actually less forbidding than it might appear, particularly in the United States.

U.S. energy consumption is not only much higher than in any other affluent economy (a reality that would make it easier to reduce it without compromising the prevailing quality of life), but the country's average per capita use of primary energy in 2010 (8.2 toe) was about 5% lower than in 1980 and no higher than in 1970! Given this reality, it is obvious that if more responsible residential zoning regulations and more demanding automotive efficiency standards had been in place the United States could have prevented the emergence of energy-expensive exurbia and the fuel wasted due to the worsening car performance, and the average per capita energy consumption could have been gradually declining. And Europe, despite its lower per capita consumption, could have also done better: Germany's per capita energy use has remained flat for a generation, but the British rate has been marginally up and the French use in 2010 was nearly 20% higher than in 1980.

Deliberate pursuit of gradual reductions of per capita energy consumption use is both desirable and achievable but it will have to be a gradual process lasting for decades and it could not succeed without redefining many entrenched practices used to measure and to judge fundamental energy realities and policies. One of its most important preconditions would be to discard the misleadingly incomplete ways of valuing goods and services without appraising their real costs (including environmental as well as strategic and health burdens) and without judging their benefit by using life cycle analyses. Although none of these ideas guides today's economic thinking, substantial intellectual foundation for such more comprehensive valuations is already in place.

And if a rapidly changing climate were to force an accelerated transition to renewable energies, then a substantial reduction of per capita energy use may be simply a key unavoidable component of such a transformation. Tellingly, an assessment of a 100% renewable energy system in Denmark concluded that even in that small and energy-efficient country (its current per capita annual energy use of 3.1 toe is about 15% below the EU mean) that goal could be achieved by 2050 only if space heating demand in buildings were reduced by half, if industrial fuel consumption declined by 30%, and if electricity demand were cut by 50% in households and by 30% in industry (Lund & Mathiesen, 2009). Similarly, MacKay (2009, pp. 212–213) ended his presentation of five plans for Britain energized by noting that "there is something unpalatable about every one of them" and that "perhaps you will conclude that a viable plan has to involve less power consumption per capita. I might agree with that, but it's a difficult policy to sell."

Difficult as it would be, reducing the energy use would be much more rewarding than deploying dubious energy conversions operating with marginal energy returns (fermentation of liquids from energy crops being an excellent example), sequestering the emissions of CO_2 (now seen as the best future choice by some industries), and making exaggerated claims for non-fossil electricity production (both in terms of their near-term contributions and eventual market shares), or hoping for an early success of highly unconventional renewable conversions (jet stream winds, ocean thermal differences, deep geothermal). After all, a dedicated but entirely realistic pursuit of this goal could result in reductions on the order of 10% of the total primary energy consumption in a single generation, an achievement whose multiple benefits could not be matched by the opposite effort to increase the overall energy use.

Affluent countries should thus replace their traditional pursuit of higher energy output and increased conversion efficiency with a new approach that would combine aggressively improved efficiency of energy conversion with decreasing rates of per capita energy use. This combination would be the best enabler of the unfolding energy transition. Until we get such history-changing conversions as reliable, inexpensive PV cells generating electricity with 50% efficiency or genetically engineered bacteria exuding billions of liters of kerosene, it is the best way to ensure that the new renewables will come as close to displacing fossil fuels as is economically advantageous and environmentally acceptable.

I believe that having in mind an ultimate goal—one that cannot be reached in one or even two generations but that would serve as a long-term inspiration—would be helpful. There is no doubt that all important quality-of-life variables (ranging from infant mortality to average longevity and from good income to ready access to education) are related to average per capita energy use in a distinctly nonlinear manner. Global data plots display unmistakable inflection zones at around 1.5 toe/capita with diminishing returns afterwards, and with hardly any further gains as average per capita consumption approaches 3 toe/capita. So perhaps the last rate could be a great long-term inspirational goal for rational, reasonably equitable, and decently prosperous societies of the future. Lower rates could be technically conceivable later in this century. Several years ago I set 60 GJ /capita, or roughly 1.5 toe and approximately the global mean of commercial energy consumption, as an ultimate goal.

Similarly, a European initiative led by the Swiss *Eidgenössische Technische Hochschule* had formulated a nearly identical goal of a 2,000-W society (Jochem et al., 2002): Annual per capita use of 60 GJ equals the power of 1,900 W. But the 3-toe economy (roughly 120 GJ/capita) is a practical goal that could be achieved by the majority of high-income countries in two to three generations. And it would be a success, and an enormous help to the unfolding shift away from fossil fuels, even if most of the affluent consumers got only halfway there. Any move in that desirable direction would have multiple, and mutually reinforcing, benefits as it would simultaneously promote the capacity to innovate, strengthen the fuel-importing economies by improving their trade balances, and reduce the burden on the Earth's environment.

Today's excessive energy use has the opposite effect—and it cannot be defended by claiming that, at least, it has made the citizens of affluent economies commensurably more satisfied with their lives. There is no evidence of this: Most notably, U.S. record shows virtually no gain in personal happiness since 1947 when the first nationwide polling was done and when the per capita energy use was nearly 50% below the current level; and, as Easterlin (2003) showed, life events in the nonpecuniary domain (marriage, divorce, and disability) are more important for the state of mind. I know that a call for reduced energy use would be widely seen as undesirable and politically unacceptable, and that its rejection would be shared across most of the modern political spectrum. This must be expected. Replacing entrenched precepts is never easy, but today's combination of major (i.e., economic, environmental, and strategic) concerns provides a nearly perfect opportunity for radical departures.

Energy transitions have been, and will continue to be, inherently prolonged affairs, particularly so in large nations whose high levels of per capita energy use and whose massive and expensive infrastructures make it impossible to greatly accelerate their progress even if we were to resort to some highly effective interventions. The overall composition of primary energy supply and the principal modes of energy conversions will closely resemble today's arrangements five or ten years from now—but how far we will advance into the post-fossil future in three or four decades will not be determined only by the commitment to innovation but also by our willingness to moderate our energy expectations and to have our energy uses following a more sensible direction, one that would combine reduced demand with a difficult, but eventually rewarding, quest for a civilization powered by renewable energy flows.

APPENDIX

Global energy consumption, 1800–2008

Year	Coal	Crude Oil	Natural Gas	Hydro Electricity	Nuclear Electricity	Biofuels	Total
1800	0.35					20	20.35
1810	0.46					21	21.46
1820	0.55					22	22.55
1830	0.95					23	23.95
1840	1.28					25	26.28
1850	2.05					26	28.05
1860	3.82					25	28.82
1870	5.91	0.02				25	30.93
1880	9.15	0.12		0.04		25	34.31
1890	13.88	0.32	0.12	0.05		24	38.37
1900	20.62	0.65	0.23	0.06		22	43.56
1910	31.16	1.43	0.51	0.12		23	56.22
1920	35.40	3.20	0.84	0.23		25	64.67
1930	36.45	6.32	2.17	0.47		26	71.41
1940	41.71	9.55	3.15	0.69		26	81.10
1950	45.37	19.60	7.53	1.20		27	100.70
1960	55.59	39.55	16.10	2.48	0.03	32	145.75
1970	62.39	85.31	35.89	4.93	0.83	34	223.35
1980	79.80	110.24	51.76	6.11	7.68	36	291.59
1990	93.70	113.74	71.07	7.78	19.10	40	345.39
2000	87.83	129.02	86.46	9.55	24.55	45	382.41
2008	132.00	141.00	104.00	11.29	26.12	42	456.41

All values are in EJ, rounded to the nearest 0.01 EJ or about 240,000 t of oil equivalent.

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